FROM THE UNDERGROUND UP:

BRINGING BONE CHAR FERTILIZER TO MARKET IN ETHIOPIA

A Thesis Presented to the Faculty of the Graduate School of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Science Applied Economics and Management

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January 2017

ABSTRACT

Nearly all phosphorus fertilizers are derived from mined rock phosphate. Rock phosphate is a non-renewable resource that is quickly depleting and increasingly controlled by a small number of countries. Recent price volatility on the world market and the risk of future shortfalls threaten food security for developing nations. In Ethiopia, bone char fertilizer is a promising alternative to imported phosphorus. This thesis explores the steps to bringing bone char fertilizer to the Ethiopian market. We investigate the bone residue supply chain, the impact of bone collecting on the income of collectors, and the quantities and cost of bone residues in Jimma, Ethiopia. Using experimental data, we analyze the costs and profitability of bone char production. Lastly, we explore the acceptability and willingness to pay for different formulations of granulated bone char fertilizer among Ethiopian farmers using a Vickery second-price auction format.

BIOGRAPHICAL SKETCH

Bourcard Nesin was born in a small town in northern Maine. He completed his bachelor's in sustainable agriculture at the University of Maine, where he researched genetics in plant pathology and organic cropping systems. Prior to enrolling at Cornell University, he ran a large-scale commercial urban farm and non-profit in South Florida.

ACKNOWLEDGMENTS

I would like to thank the following people that made this research possible:

- My advisor and the leader of the research team, Dr. Garrick Blalock, for the opportunity to be on the ground in Ethiopia and the freedom to develop my research skills
- Dr. Andrew Simons, for the long hours he devoted to my work, which was above and beyond what anyone would have expected of him
- Dr. Berhanu Belay for his patience when I blundered and his support in navigating a very complicated financial system.
- Milkiyas Ahmed, Yared Tadesse and Henok Atile who have become life-long friends and who have proved themselves as deserving of every opportunity they can get their hand on
- The soils team of Dr. Johannes Lehmann and Dr. Dawit Solomon for their relentless optimism, and Kelly Hanley for her air drops of all things necessary
- Dr. Calum Turvey, for helping me (re)discover the joy of (re)writing
- My distractible friends, Pietro Spini and Jin Yan, who entertained my gripes and lamentations and answered many a modeling question
- My partner, Lea Stagno, for her undying support and patience as I moved abroad and back again with dizzying regularity

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Chapter 1: Introduction

With the exception of nitrogen (N), Phosphorus (P) is the most important nutrient in agricultural production. In crop development, P is critical for flowering, fruiting, maturation, root development and cell division (Brady, 1984). Unlike nitrogen, which can literally be pulled from the air (Erisman, Sutton, Galloway, Klimont, & Winiwarter, 2008), commercial phosphorus fertilizers are derived almost exclusively from mined rock phosphate, which is finite and non-renewable (Vassilev, Martos, Mendes, Martos, & Vassileva, 2013). Demand for phosphorus is expected to double by 2050, but there is mounting evidence that the world's supply of rock phosphate around is under threat (Chowdhury, Moore, Weatherley, & Arora, 2017). If the supply of P fertilizer were limited, it would represent an existential threat to food security around the world, but most particularly in Africa where the poorest farmers face the highest fertilizer prices and the highest rates of food insecurity (Dana Cordell & White, 2014).

1.1 The two-fold phosphorus problem

The threat to P fertilizer supply is two-fold. Firstly, three countries control between 82% and 94% of the world's mineable phosphate rock reserves (Obersteiner, Peñuelas, Ciais, van der Velde, & Janssens, 2013; USGS, 2015). Any interruption in the supply of rock phosphate from any one of these top-producers would have repercussions on P prices and availability around the world. The second component of the threat is that the world may soon reach peak P extraction after which mined P supplies will begin to decline. In the following section, we will discuss each threat in greater detail as well as ways to mitigate the impact of the oncoming crisis.

1.1.1 Oligopoly and price volatility

The three countries that control the vast majority of P rock reserves are China, Morocco and the United States, with Morocco alone controlling as much as 85% of the world's reserves (Obersteiner et al., 2013). To bring into context the level of control that these three countries exert on the supply of P rock, we can look to the world's most famous oligopoly, the Organization of Petroleum Exporting Countries. Famous for being able to impact world supply and prices, OPEC consists 13 countries that combine to control 81% of the world's oil reserves (OPEC, 2016).

Figure 1.1 Morocco, China and the U.S. control as much as 94% of the world's rock phosphate reserves

The concentration rock phosphate reserves and production creates short-term risks that affect all countries without significant mineable reserves. In 2008, for example, the Chinese government, with the intention of preserving the country's depleting domestic supply, imposed a 135% export tariff on rock phosphate. China, at the time, had the world's highest annual mining production (USGS, 2009). Their unilateral change in policy contributed to an 800% spike in world phosphorus prices, which in turn contributed to the 2008 food shortages that caused severe food crises in 47 countries, 27 of which were in Africa (Chowdhury et al., 2017). When P prices rise so quickly, poor farmers, already unable to afford P fertilizer, are unable to compete with producers in richer countries for the available P supplies and are forced out of the market (Dana Cordell, Drangert, & White, 2009). This once again demonstrates that the countries that will be most acutely affected are poor countries with no mineable reserves of rock P.

1.1.2 Peak Phosphorus

The estimates for life span of the world's remaining rock phosphate reserves lies between 70 and 370 years (Chowdhury et al., 2017; Dana Cordell et al., 2009; Dana Cordell & White, 2014; Von Kawenbergh, 2010). As reserves decrease, P supply will likely also drop, causing an increased P fertilizer price (Chowdhury et al., 2017). Figure 2 shows the various estimates for the year at which peak phosphorus will occur.

The two problems outlined above are complementary in nature, such that as a country's domestic P reserves are depleted, they become increasingly dependent on Morocco or another exporter for the totality of their P supplies. One possible outcome would be a world fully dependent on trade with Morocco for rock phosphate, "where press-reports have emerged of Dubai-style luxury developments being planned in anticipation of future windfalls" from rising rock P prices (Elser & Bennett, 2011).

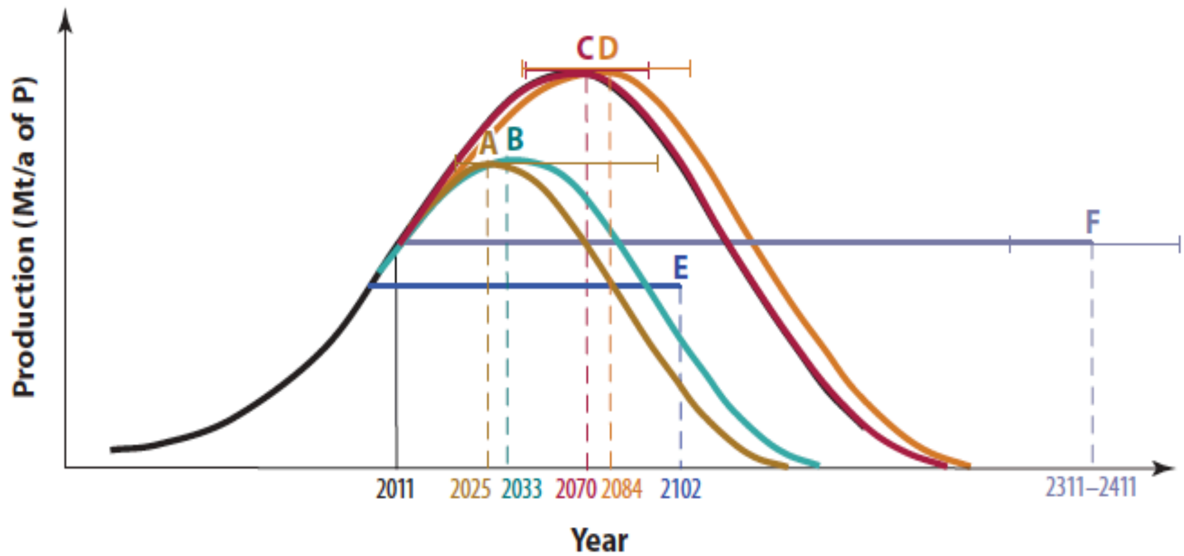

Figure 1.2 Various estimates for the occurence of Peak P, from (Dana Cordell & White, 2014)

1.1.3 Alternatives to rock phosphate

There are many ways that developing countries can deal with the oncoming shortfalls, power imbalances and price changes in the global market for phosphorus. Indeed, there are a great many steps that must be taken to ensure that there is sufficient P for agricultural production as P rock becomes increasingly scarce. The principal component of creating a sustainable scenario for meeting future P demand is an across-the-board increase in P use efficiency (D. Cordell, Rosemarin, Schröder, & Smit, 2011; Dana Cordell et al., 2009; Dana Cordell & White, 2014). While efficiency will reduce the quantity of P fertilizer required for agricultural production, it will not fertilize crops. The actual P fertilizer of the future will have to come from recovered sources, such as human and animal wastes (Beardsley, 2011). Each country without mineable P faces an increasingly urgent imperative to identify an exploitable and abundant domestic source for recycled P. In Ethiopia, the country with the largest animal herd in Africa, that domestic source may just come in the form of animal bones (Biffa, Bogale, & Skjerve, 2010; A. Simons, Solomon, Chibssa, Blalock, & Lehmann, 2014).

1.2 Ethiopia and the case for bone char fertilizer

Ethiopia's animal herd produces 190-330 million kg of bone residues every year, which contain 9-11% elemental P (A. Simons et al., 2014). The animal bones, byproducts of meat consumption and animal husbandry, contain as much P as 84,290-176,937 metric tons (mt) of chemical P fertilizers such diammonium phosphate (DAP) and triple superphosphate (TSP). The phosphorus in bones could displace 25%-52% of annual imported phosphorus fertilizers from the year 2014 (FAOSTAT, 2014)[1].

There is no commercial outlet for animal bone residues in Ethiopia, and the disposal of bones represents a real cost to businesses in the meat supply chain. Bones were once used as animal feed, but the risk of spreading bovine spongiform encephalopathy (BSE, or mad cow disease) has ended the practice (Jeng, Haraldsen, Grønlund, & Pedersen, 2007). Many bones, improperly disposed of by butcher shops and restaurants, find their way into public green spaces, are burned in makeshift incinerators or else tossed, haphazardly, into the streets. Capturing bone residues from the waste stream will not only provide fertilizer, but also improve public health via the removal of potential hazardous biological material from public areas.

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[1] Imports do not equal consumption. Due to a mismatch of imports and demand, the typical consumption of fertilizer is 33% of imports, with a significant consumption from the previous year's carry-over stocks (Heffernan & Ariga, 2012; Rashid, Tefera, Minot, & Ayele, 2013). The data

Bone meal is an effective fertilizer (Chen, Helenius, & Kangas, 2011; Jeng et al., 2007; Mondini et al., 2008; Römer, 2006). It is more efficient and has a higher P concentration than rock phosphate (Bekele & Höfner, 1993; Zwetsloot, Lehmann, & Solomon, 2015). Despite its value as a fertilizer, selling bone meal without further processing presents a number of problems. Raw bone, if improperly stored, can produce unpleasant odors. These same odors, while offensive to humans, will likely attract hyenas. The spotted hyena (*Crocuta crocuta*), which has a range throughout Ethiopia, survives almost exclusively on anthropogenic animal wastes (Yirga et al., 2015). By applying bone wastes to fields, there is a chance of attracting hyenas to farmers' homes. While the actual risk of hyenas may be low, the perceived risk of hyena attacks "still has resonance in rural Ethiopia" and may pose a significant obstacle to the adoption of unprocessed animal bone as fertilizer (Gade, 2006). Lastly, there is a risk that contaminated animal tissue could be eaten by farm animals, potentially spreading BSE and other diseases (Cummins & Adkin, 2007)

By converting animal bones into bone char, all of these problems can be resolved. Bone char is produced via pyrolysis, a process in which bone meal (a slaughterhouse waste) is placed inside a chamber with limited oxygen and heated in excess of 400° C. Pyrolysis does not require any expensive equipment and all the materials required for manufacturing the equipment used in pyrolysis can be sourced locally and the equipment inexpensively built in domestic machine shops. Pyrolysis sterilizes the product, preventing the transmission of diseases associated with raw animal products (Warren, Robinson, & Someus, 2009), eliminates unpleasant odors, and increases the concentration of desirable nutrients like P and calcium (Ca) (Zwetsloot et al., 2015) Laboratory analysis shows that bone char contains 14-16% of elemental P, which is 68%-78% of imported chemical fertilizers such as DAP and TSP (Zwetsloot et al., 2015). During the length of this paper, we will consider bone char to be 14% P with a chemical analysis of 0-32-0 (NPK).[2]

Bone char has other desirable properties, beyond its P content. While rock phosphates contain heavy metals, such as cadmium, lead, copper, and arsenic, these contaminants are not detected in bone char (Vassilev et al., 2013). Not only does bone char have insignificant levels of heavy metals, applying bone char is an effective tool for reducing heavy-metal contamination of food grown on contaminated soils. Other P fertilizers, such as TSP and DAP, are highly water-soluble. While they are very effective in providing P at a crucial time for crop development, that P can become less available to crop plants over time (Kucey, Janzen, & Leggett, 1989). Bone meal or meat and bone meal are not quickly available to crop plants (Warren et al., 2009) Bone char is more rapidly available than untreated bone meal, but lasts long in the soil than TSP of DAP (Warren et al., 2009; Zwetsloot et al., 2016). Bone char's P-supply characteristics are, therefore, between traditional slow-release and fully soluble fertilizers (Warren et al., 2009). More than 40% of Ethiopian farmland is overly acidic (ATA, 2013). Chemical amendments are often needed to correct the pH on highly acid, P-fixing soils in Ethiopia, but lime fertilizer is not commercially available (Taddese, 2001). Bone char has a 13% calcium carbonate equivalent[3], which increases soil PH, thereby increasing the availability of essential plant nutrients, such as P (Atkinson, Fitzgerald, & Hipps, 2010). DAP, the only other phosphorus fertilizer available in Ethiopia contributes to the further acidification of soils (Brady, 1984). Fertilizer imports are consuming precious foreign currency reserves in Ethiopia. Locally produced products could

[2] This is the independently verified chemical analysis of bone char produced and pelleted by our research team with a locally built pyrolysis kiln and locally procured ingredients. See appendix A.

[3] The acid-neutralizing capacity of a material relative to pure calcium carbonate. This result was taken from a lab result that can be seen in appendix A.

reduce the current practice of rationing foreign currency, which negatively affects exports, local production of import substitutes and generates high rents for non-poor populations (Dorosh, Robinson, Ahmed, & others, 2009).

1.3 Research objectives

The body of this thesis begins with a literature review (**Chapter 2**). The review will present information on the fertilizer value chain in Ethiopia as well as a model for fertilizer demand that is vital to understanding the context in which our research is being performed

Following the literature review, we will investigate three areas that are vital to bringing bone char fertilizer to the market in Ethiopia: the bone residue supply-chain, bone char fertilizer production and profitability, and marketing experiments. In our work investigating the bone residue supply chain (**Chapter 3**), we use a collection experiment to determine the viability of hiring a large group of urban and peri-urban poor to collect bones from within the municipality of Jimma, Oromia, Ethiopia. We leverage the collection experiment to determine the per kilogram price for bone residues, the quantities of bone residues that can be collected and to perform a randomized control trial on the effects of entrepreneurship training on income and collecting practices among participants. We then use data from the collection experiment as well as data from producing bone char in locally built equipment to determine the costs of bone char production (**Chapter 4**). We use the results of the cost analysis exercise to compare the costs of bone char to imported fertilizers as well as generate a model for maximizing the profit of a bone char fertilizer producer. In the last area of investigation, we use experimental auctions to determine the demand for bone char fertilizer among Ethiopian farmers (**Chapter 5)**. The goal of the experimental auctions is to establish that there is no acceptability constraint associated with granulated bone fertilizers, as well as determine the discrete characteristics and nutrient profiles that drive farmer fertilizer valuations. Lastly, we present a conclusion of our research and areas of investigation that require additional resources (**Chapter 6).**

Chapter 2: Literature review

The following section is a summary of information that is critical for contextualizing the environment in which our research was conducted. In addition to discussing the current status of fertilizer consumption and the fertilizer value chain in Ethiopia, we will discuss the very interesting history of bone fertilizers and generate a simple model of farm-level fertilizer demand.

2.1 The long history of bone-based fertilizers

One inspiration for researching bone-based fertilizer in Ethiopia came from a study of indigenous soil management systems in West Africa, in which a centuries-old tradition of applying bones and other organic waste transformed "infertile and carbon-poor humid tropical soils into long-lasting, fertile, carbon-rich and productive soils capable of supporting intensive agriculture in an ecologically and socially sustainable manner" (Solomon et al., 2016). The intentional application of bones as a soil management strategy resulted in treated fields having 5-270 times more plant-available P than adjacent soils (Solomon et al., 2016). In fact, the effect of discarded and decaying bones has such long lasting effects on the phosphate levels in soil that raised P levels has been used in anthropological research as an indicator for prehistoric human settlements (Solecki, 1951).

The historical use of bones as fertilizer is not isolated to Africa. Bones were an important agricultural input that factored into the agricultural revolution in 19th century Britain.

Individuals called “rag-and-bone men” or “bone-grubbers” would go door-to-door scavenging bones and household wastes for resale throughout the United Kingdom. The German chemist Justus von Leipig complained that English merchants, in their insatiable appetite for bone were “rifling the battlefields of Europe and ransacking the catacombs of Sicily.” (Thompson, 1968). The long-term benefits of the application of bone residues to agricultural land was so prized and highly regarded that it gave rise to the famous "Lincolnshire tenant-right", a set of customary rules for compensating outgoing tenants for the unexhausted improvements provided by their bone meal applications (Thompson, 1968). Even the most utilized sole-nutrient phosphorus fertilizers in the world carry a mark from the times of widespread bone fertilizer usage. The prefix “super” in super phosphate and TSP originally referred to the improved fertilizer quality of bones soaked in sulfuric acid over untreated, crushed bones, a practice that started in the 1840’s (Roy, 2006; Thompson, 1968). Eventually, bones were supplanted by imported guano from south America and, later, super phosphate derived from rock P (Thompson, 1968).

2.2 Fertilizer use in Ethiopia

Despite having some of the most depleted soils in Sub-Saharan Africa, fertilizer adoption among smallholder farmers in Ethiopia is very low (MOA, 2010; Spielman, Kelemwork, & Alemu, 2012a). Estimates for the percentage of farmers using fertilizer range from 30% (Spielman et al., 2012a) to 50% (Headey, Dereje, & Taffesse, 2014; Moller, 2015). The principal constraint to adoption of fertilizers are high prices (~40%) (Moller, 2015). Indeed, Africa has the highest fertilizer prices in the world though the farm gate price of fertilizers in Ethiopia is slightly lower than its neighbors (Rashid, Tefera, Minot, & Ayele, 2013). If bone char fertilizer can be produced more cheaply than imported fertilizer, it may significantly increase demand.

The second most important constraint to fertilizer adoption in Ethiopia is availability and the mismatch between when farmers need fertilizer and when fertilizer shipments arrive, with 32% of farmers naming one or the other as the principal constraint to fertilizer adoption (Moller, 2015). Fertilizers are imported from China through the Djibouti Port, 950 km from Addis Ababa, after which they are diverted to regional warehouses for distribution (Heffernan & Ariga, 2012). There are many opportunities for delay along the poor infrastructure from Djibouti Port to the final user. Locally produced bone char fertilizer, having to traverse a shorter distance and crossing no international boundaries, is not going to encounter the same problems and delays in transit.

At the time of this study, there are only two commercially available chemical fertilizers in Ethiopia: urea (46-0-0) and DAP (18-46-0). For 2014, the last year that import data is available, a total 340,300 mt of DAP and 380,100 kg of urea (FAOSTAT, 2014). There are no sole-nutrient P fertilizers in Ethiopia, which presents a challenge to marketing bone char directly to farmers. Introducing a novel fertilizer into a market with a narrow range of products, such as in Ethiopia, can result in limited adoption and demand for the new product, a consequence of a lack of knowledge of the benefits of the product (Heffernan & Ariga, 2012). Generating appropriate fertilizer blends, improved marketing strategies via agro-dealers and capacity building among extension agents are just a few ways to overcome such a limitation (Heffernan & Ariga, 2012).

2.3 The fertilizer market and value chain in Ethiopia

Except for a short period between 1996 and 2002, state-run actors have always had total control of fertilizer markets in Ethiopia (Heffernan & Ariga, 2012; Jayne, Govereh, Wanzala, & Demeke, 2003; Rashid et al., 2013). Ethiopia's fertilizer market has high transaction costs in marketing and distribution and a geographically dispersed small farmer population with limited financial resources and limited access to credit (Heffernan & Ariga, 2012). This renders the fertilizer market in Ethiopia is very "thin" (Anderson & Masters, 2009). In a country whose real GDP growth averaged 10.9 percent between 2004 and 2014, the opportunity costs of private-sector capital is too high (Moller, 2015). Additionally, state-run holding companies have previously received high levels of governmental support and policy privileges (Rashid et al., 2013). For example, it has been reported that farmers receiving government fertilizer credits were not allowed to purchase from private actors (Demeke, Guta, & Ferede, 2004). With such a perilous fertilizer market environment and the rapidly expanding economy in Ethiopia generating high returns opportunities, it is no surprise that no private firm has had a share of the fertilizer market since 2002.

In its current form, the fertilizer value chain in Ethiopia consists of three general activities: import planning, import execution and lastly, marketing and distribution (Rashid et al., 2013). The import-planning component begins with a demand assessment at the *woreda*[4] level. The demand assessments are aggregated at the regional level and sent to the Bureau of Agriculture and Rural Development (BoARD). BoARD then sets imports requirements by subtracting the

[4] *Woreda* is the second-smallest level in the hierarchy of government in Ethiopia. *Woredas* are composed of multiple *kebeles*.

previous year's carry-over stocks from the aggregated regional level demand estimates (Rashid et al., 2013). Import-execution is performed exclusively by the state-owned Agricultural Input Supply Enterprise (AISE). The logic of this monopoly power is to take advantage of economies of scale and the bargaining power of a single state actor (Rashid et al., 2013).

Starting in 2008, AISE has worked exclusively with regional farmers' cooperative unions in order to market fertilizers. The unions, upon receiving shipments from AISE, distribute supplies to their primary cooperative members. The primary cooperatives typically receive fertilizer on credit from unions and sell, mostly in cash, to smallholder farmers. In areas not covered by cooperative unions, AISE takes responsibility for delivering fertilizers (Rashid et al., 2013).

BoARD is responsible for determining prices and margins all along the value-chain, exerting control on virtually all costs and credit issues from the importation process to the farmer financing (Rashid et al., 2013). Under the current system, profits along the fertilizer value chain in Ethiopia for account for 10% or less of the marketing cost (Jayne et al., 2003). Lastly, approximately 60% of farmers in Ethiopia have to borrow money in order to purchase fertilizer (Rashid et al., 2013).

With the level of state control over fertilizer distribution and credit, it is difficult to envision a scenario in which a private fertilizer producer could successfully integrate their product into the fertilizer supply chain of Ethiopia without explicit support and consent from the Ethiopian government. The chance to insert bone char into this highly controlled value chain may come in the form of Ethiopia's new fertilizer blending program. To better meet fertility requirements and improve fertilizer use efficiency, the Ethiopian government is opening fertilizer blending facilities in all the major growing region of the country (ATA, 2014). As part of this new program, Ethiopia has begun importing new fertilizer ingredients, which will include sole-nutrient P fertilizers, for the first time in more than four decades. Convincing the government to purchase bone char fertilizer for its new blending program may be one alternative to an otherwise complex and high-risk independent entrance into Ethiopia's fertilizer market.

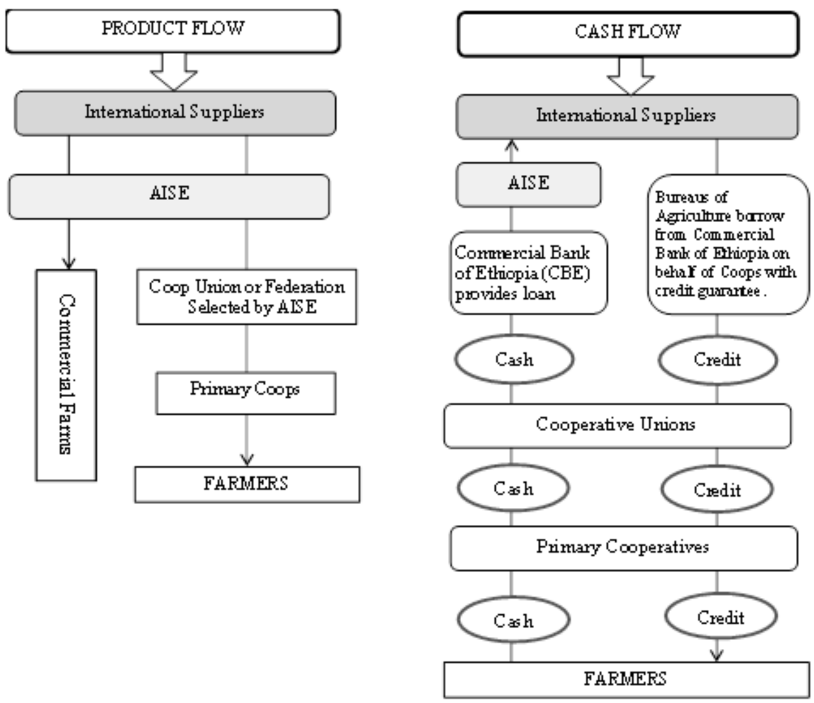

Figure 2.1 Product and cash flows in Ethiopian fertilizer value chain (Rashid et al., 2013).

2.4 The yield response function and farm-level demand for fertilizer

The demand for fertilizer, in the absence of market failures, depends on the profitability of fertilizer use. In Ethiopia, however, it is hard to deny the presence of market failures (Dillon & Barrett, 2014; Rashid et al., 2013). One example of a common market failure in Ethiopia is a farmer's lack of knowledge regarding the benefits or risks of using fertilizer leading the farmer to make a potentially irrational decision. These market failures undoubtedly contribute to the low adoption rate of fertilizer in Ethiopia. On the other hand, it is not clear to what extent fertilizer use rates are sub-optimal, given the output prices, transaction costs and risks associated with rain fed agriculture (Dillon & Barrett, 2014; Marenya & Barrett, 2009). As a consequence of these risks, it is commonly argued that each dollar spent on fertilizer in Sub-Saharan Africa, must generate at least two dollars of additional yield in order for fertilizer use to be a rational decision (Rashid et al., 2013; Spielman, Kelemwork, & Alemu, 2012b). The exact profitability of fertilizer, however, is dependent on farm-level characteristics such as location, market access and credit availability (Rashid et al., 2013)

In order to build a production function with farm-level fertilizer demand dependent on profit, we must start with a yield response function, $Y(x_f)$. Commonsense tells us that output (Y) rises with the amount of fertilizer applied to the field (x_f) but at a decreasing rate, which would indicate that a quadratic function is the most appropriate functional form.

$$Y(x_f) = a + bx_f - cx_f^{\,2} \qquad \text{Eq. 2.1}$$

Equation 2.1 gives us the farm's output or crop yield with respect to fertilizer applications. If we assume that fertilizer is the only factor in crop production, in order to calculate profits (π), we need only to multiply output, $Y(x_f)$, by the crop price, P, which represents revenues and subtract the total cost of the fertilizer, rx_f. For the sake of simplicity, we do not include a risk component in the equation.

$$\pi = PY(x_f) - rx_f = P(a + bx_f - cx_f^{\,2}) - rx_f \qquad \text{Eq. 2.2}$$

The rational farmer will continue to apply fertilizer until the marginal revenues of one more unit of fertilizer is equal to the marginal costs of one more unit of fertilizer. To find the point at which this occurs, we take the derivative of the profit function and set the equation equal to zero.

$$\frac{d\pi}{dx_f} = 0 = bP - 2cPx_f - r \qquad \text{Eq. 2.3}$$

Solving for x_f^{*}, the profit maximizing quantity fertilizer, gives equation for the farm level demand for fertilizer:

$$x_f^{\,*} = \frac{bP - r}{2cP} \qquad \text{Eq. 2.4}$$

Equation 2.4 tells us that a rational farmer, independent of risk and other inputs, will continue applying fertilizer until marginal profits are equal to zero. In other words, the quantity of fertilizer at which the value of the marginal physical product is equal to the cost of an additional unit of fertilizer is the rational farmer's demand for fertilizer, *ceteris paribus.*

Chapter 3: Securing primary inputs: The bone residue supply chain

In the following chapter, we will describe an experiment conducted in Jimma, Ethiopia. The principal goal of the experiment was to determine the feasibility of mobilizing a labor force to intercept bone residues from the waste stream within the municipality. We presented "permits" to 95 individuals in Jimma, Ethiopia and purchased bones from collectors at researcher-determined per-kilogram price. We also leveraged bone-purchasing activities to perform a randomized control trail (RCT) in which participants were placed into a treatment and control group. The treatment group, in addition to receiving a permit, received a modified Start and Improve Your Business Training (ILO, 2011) with specific exercises and examples for a bone collecting enterprise while the control group only received a permit. The goal of this randomized control trial was to determine if entrepreneurship training could improve the well being of collectors as well as increase the total amount of bone residues they sold to the researcher-run collection site.

The research program presented a number of ethical, organizational and institutional challenges. For example, the original research program was meant to last six weeks with 200 participants, but the actual trial lasted ten days[5] with only 95 participants. The challenges and obstacles that we encountered during the program revealed important insights for both our research questions and issues of research practice in general.

[5] The time between the baseline and follow-up interview was 6 weeks, due to unexpected difficulties, bones residues were purchased over a 10-day period from January 25, 2016-February 3, 2016

3.1 The current bone residue supply chain

In Ethiopia, the only place to buy bone meal (rendered animal bone) is the municipal abattoir in Addis Ababa, and they have expressed interest in providing bone residues to a bone char fertilizer industry. Nibret Beka Fanta, the managing director of the Addis Ababa Abattoirs Enterprise (AAAE), has expressed enthusiastic support for a partnership, saying slaughterhouses are "facing huge pressure in solid-waste disposal and... demand from the government to covert raw bone wastes into useful products." The manager explained that meat and bone meal had previously been sold as animal feed, but the high risk of transmissive spongiform encephalopathies, like bovine spongiform encephalopathy (BSE, more commonly known as "mad cow disease") has virtually ended the practice[6]. Instead, government-run abattoirs such as the Addis Ababa Municipal Abattoir, the largest in Ethiopia and run by the AAAE, must pay municipal waste management to discard the bones. The work of disposing of bone waste has generated tension between the abattoirs and municipal waste management, who claim that bone collection generates undue risk to collectors[7].

At the time of publication, there is no large-scale commercial outlet for the animal bone waste generated by abattoirs in Ethiopia. A partnership with these government-run slaughterhouses, therefore, may represent an easy way to gather bone residues for bone char fertilizer production.

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[6] Due to risk of BSE transmission, the European Union has banned the use of meat and bone meal as livestock feed, forcing producers to find alternative commercial outlets of the byproduct (Jeng, Haraldsen, Grønlund, & Pedersen, 2007)

[7] The complaint from municipal waste management is not altogether unfounded, as waste collectors already face a high number of occupational hazard, of which biological agents (bones) are among the most dangerous (Bleck & Wettberg, 2012)

Using only bones sourced from municipal abattoirs for bone char fertilizer production, however, presents a number of problems.

When the Addis Ababa Municipal Abattoir was selling bone residues for animal feed, our research team was able to purchase sterilized product for 10.50 ETB per kilogram. During pyrolysis, the bones lose approximately 30% of their mass by weight. Accounting only for the cost of bone meal and the loss of mass during pyrolysis (adding no costs for production, processing, transport or profits), bone char produced from bones purchased from municipal slaughterhouses would cost 13.65 ETB per kilogram. To bring this price into perspective, the farm-gate price for diammonium phosphate (DAP), which contains 30% more P per kilogram and is 18% nitrogen[8] is 15 ETB. With the price of bone meal at 10.50 ETB per kilogram, it is difficult to envision an economically viable path to the commercialization of bone char fertilizer in Ethiopia.

It is possible that a private company interested in producing bone char fertilizer could negotiate with the government-run abattoirs to obtain a lower price for bone residues. Beyond any initial contract, however, the slow-paced bureaucracy of the abattoirs is unlikely to adjust prices to changes in the market and the abattoirs' monopolistic control of bone residues generates a lot of uncertainty with respect to the long-term availability of bone residues for fertilizer production. Additionally, the bones accumulating in abattoirs represent a small proportion of the total animal bone wastes generated in the country. The only bones remaining in the abattoir are skulls, backbones, pelvises and the lower leg (fibula, tibia, metatarsal, and metacarpal), the rest of the bone mass is sent along with the carcass to for further processing.

[8] See Cost Analysis, Chapter 4

Figure 3.1 Worker removes hide from metatarsal/metacarpal at Hawassa Municipal Abattoir

Most bones accumulate during butchering (meat processing) rather than the slaughtering process (Ockerman & Hansen, 2000). Unlike the United States, where large-scale meat processing facilities serve as a major accumulator of bone wastes, Ethiopian meat processing is performed by small-scale butcheries, which are widely distributed throughout each community[9]. Butcher shops and the restaurants, like abattoirs, have no commercial outlet for bone residues. We have observed butcher shops burning bone wastes, dump them into rivers (which are often used for bathing and other domestic uses), or otherwise dump them into empty green spaces that are often used for recreation. Indeed, it is nearly impossible to walk down any street in Ethiopia without seeing bone waste strewn alongside the road with surprising regularity.

[9] Mekelle is a small city in the Tigray region. The city has a small government run abattoir, ~200,000 inhabitants, and 110 registered butchershops (Haileselassie, Taddele, Adhana, & Kalayou, 2013). Jimma can be expected to have a similar number of butcher shops.

If the impact of a bone char industry on P fertilizer supplies in Ethiopia is going to be maximized, the bone residues that accumulate at butcheries, restaurants and dumpsites must be recovered. Furthermore, being able to pay individuals to collect bone wastes from sources downstream of abattoirs will diversify the supply chain and generate a real market price for bone residues. These activities, in addition to securing additional resources for fertilizer production, may put pressure on abattoirs to adjust their own prices as opposed to charging the somewhat arbitrary and unchanging value of 10.50 ETB. In addition to providing the primary material to a bone char fertilizer industry, the recapture of bone residues from the waste stream would require a large labor force, which would likely be comprised of individuals from Ethiopia's most at-risk communities. If all of the 190,000-330,000 mt of bone residue generated in Ethiopia annually were collected at 1 ETB, the bone residue supply chain could generate enough income to support hundreds of thousands of individuals across the country at income levels commensurate the per capita national income of $590 USD (World Bank, 2016). Lastly, collecting bone waste has another, though difficult to quantify benefit: the removal potentially hazardous biological wastes from public areas.

3.2 Estimation of bone wastes generated in Jimma, Oromia

Our research was conducted in Jimma, Oromia, the largest city in Southwestern region of Ethiopia. As of 2007 census, the population of Jimma was 121,000 inhabitants (CSA, 2007), but was likely near 150,000 individuals at the time of our study. Jimma has a newly constructed, municipal abattoir on the outskirts of the city. According to the veterinarian that manages the abattoir, 50-60 cattle are slaughtered per day, as well as 10-20 shoats (sheep and goats). Based on the bone mass generated by each animal, this would result in the generation of 1040-1900kg of bone (A. Simons et al., 2014). Ethiopian law requires that all cattle and shoats be slaughtered in municipal abattoirs, where a pre- and post-mortem inspection can be performed. While this law typically observed for cattle, the majority of shoats used in restaurants and butcher shops, by a wide margin, are slaughtered privately, outside the abattoir[10]. Additionally, animals are slaughtered regularly for private religious celebrations, weddings, birthdays and other events. It is not uncommon for an entire cow to be slaughtered for a celebration, or multiple sheep to be consumed for a single Ethiopian Orthodox family's *Fasika* celebration or a Muslim family's evening feasts during Ramadan. We estimate that as much as 80% of shoats and 20-40% of cattle are slaughtered outside of the municipal abattoir (Dr. B. Belay, personal communication, January 20, 2016). With this extra-abattoir slaughtering activity the estimate for bones wastes generated per day rises to 1400-3250 kg[11].

It is also worth noting that sales account for only 40% of the off-take rate of cattle in the Oromia region (Negassa & Mohammad, 2007). Cattle are often used as a financial windfall as well as draft animals. As a consequence, the majority of cattle either die on the farm (51%) or else are slaughtered on the farm (5%), the implication being that bone residues entering the waste-stream are not necessarily derived from commercial slaughtering and processing (Negassa & Mohammad, 2007)

[10] While this information was verified from a personal conversation with Dr. Berhanu Belay, who has a PhD specializing in Ethiopian livestock, I have personally observed this law being violated. Sheep are brokered on street corners where butcher shop owners will purchase the animal and slaughter it "in-house".

[11] This lower-bound estimate is calculated by multiplying the lower-bound estimate of the number of cattle and shoats consumed daily in Jimma (60 and 50, respectively) and the lower-bound estimate of bone mass generated from each (20 kg per cattle and 4 kg from shoats). The upper bound is calculated by multiplying the upper-bound estimate of cattle and shoats consumed daily in Jimma (100 and 50, respectively) and the upper-bound estimate for the bone mass generated by each animal (30 kg for cattle and 5 kg for shoats). The estimates for the bone mass generated by each animal was taken from Simons *et al.* (2014).

Another way to estimate the bone wastes entering the waste stream is by analyzing the bone mass in municipal waste. In Jimma, an average of 88,000 kg of solid waste is generated every day, 4.7% of which is bone residues (Getahun et al., 2012). These numbers suggest that there is an average of 4136 kg of new bone residues entering the waste stream on a daily basis in Jimma, significantly more than our calculations generated from meat consumption. If 4136 kg of bones enter the waste stream daily (~1.5 million kg annually), and those bones have had no productive use during many years, it is reasonable to assume that there are millions of kilograms of bones spread across the municipality with varying degrees of accessibility.

If it is true that decades of bones are laying about in dumpsites and green spaces across Jimma, as we believe to be the case, it could take years to reach a point at which the generation of bone wastes has a significant effect on supply. That is, if there are millions of kilograms of easily accessible, years-old bones sitting at the city dump and along roadsides, collectors are unlikely to rely on newly generated residues for collection activities. Until these reserves are depleted and an equilibrium is reached such that the number of bones available for collection is subject to bone waste generation around Jimma, we can not know with great certainty, the long-term availability of bone residues for bone char fertilizer production.

3.3 Experimental design

3.3.1 Creating an entrepreneurial opportunity with permits for bone collection

The primary objectives of the research was to determine if a labor force could be mobilized to collect animal bones in Jimma, and if so, how many bones and at what price could bones be collected from the businesses and waste sites downstream of the municipal abattoir in Jimma. The method for bone purchasing was simple: participants were given a permit with a unique number that they could present in order to sell bone residues to a researcher-run redemption center. Each transaction (bone mass and payout) was recorded alongside the permit number associated with the individual involved in the transaction.

Scavenging, which is the best way to conceptualize the work of collecting bones, is a common activity in Ethiopia[12] (Bjerkli, 2013; Tilaye & van Dijk, 2014), and "plays an important role in promoting indigenous entrepreneurship and use of indigenous resources" (Tilaye & van Dijk, 2014). In Jimma, there is a group of child-workers called *keraliou* (pronounced: *kər-al-ē-ou*). These individuals scavenge metal scraps or plastic bottles and sell them at a pre-determined price[13]. This system for *keraliou* is identical to the mechanism through which we intended to purchase bones, and early on in the research program, some Ethiopian collaborators suggested these child workers as potential participants. Given that the International Labor Organization considers scavenging one of the "worst forms of child labor" (Saranel, 2007) and for other

[12] Scavenging is defined by the International Labor Organization as "manual sorting and picking of recyclable/reusable materials from mixed wastes at legal and illegal landfills, dumpsites, street bins and piles, and transfer points." (Saranel, 2007)
[13] A common complaint against the *keraliou* is that they would steal the nails that hold the corrugated metal fencing surrounding middle-class homes in Jimma, forcing local guards to chase them away.

obvious reasons, we elected to enroll only adults into our research program[14]. We were confident, however, that the work of scavenging and the means by which scavengers are compensated are universally understood among members of the community.

The permit is the key to the entrepreneurial opportunity. If the price we offer for bone residues is not too low, the permit generates an economic rent for the permit holder. The permit holder can choose to sell bones they collected personally or else they can leverage the rent generated by their permit to purchase bones from non-participants at one price and resell them to researchers at a higher price. By issuing permits, we have essentially given collectors the opportunity to become middlemen.

It may seem like an unusual approach to collecting. The alternative would have been simple: open a storefront and start purchasing bones from anyone who wished to sell them. By restricting enrollment, however, we are able to study collectors. Also, there may be some benefits of having middlemen within an informal supply chain. In discussing informal supply chains for recycled materials in Indonesia, Tuori (2012) posits, "by providing transportation and storage of materials, middlemen contribute to the efficiency of the supply chain that, through a decentralized network... can aggregate materials from a large number of dispersed locations to a few centralized locations."

[14] It was also suggested that we use recent university graduates for bone collecting. While we were sure that this was not our target population, it speaks both to the difficult of finding work for recent graduates as well as the general acceptance of this kind of work in the research area.

3.3.2 Adding a training component to the experiment

In addition to exploring the bone residue supply-chain, we decided to leverage the collection activities to perform a randomized control trial (RCT) exploring the impact of entrepreneurship training on income and well-being of bone collectors as well as the impact on the number of bones they are able to sell to researchers. Entrepreneurship training is a form of management training that has been administered to millions of individuals in the developing world. The aim of entrepreneurship training is improving the practices of small-business owners so that they are able to create and sustain better employment opportunities (ILO, 2011). These programs are often offered to individuals called subsistence entrepreneurs or survivalist entrepreneurs that run businesses with little growth potential but whom could benefit from improved business practices (Berner, Gomez, & Knorringa, 2012; Valerio, Parton, & Robb, 2014). Put more in the most stark terms, the goal of the training is to help "a large number of people become a little less poor" (Berner et al., 2012).

One form of entrepreneurship training, the ILO's Start and Improve Your Business training, has been administered to 4.5 million individuals in over 95 countries from 1996-2011[15]. Recent studies of training programs have been unable to show meaningful changes in profits or revenue among trainees (Giné & Mansuri, 2014; Karlan & Valdivia, 2011; Mano, Iddrisu, Yoshino, & Sonobe, 2012). Many of the experiments, however, have been directed at owners of established businesses, which may not be the optimum target population for entrepreneurship training. De

[15] [15] ILO. Start And Improve Your Business (ILO Technical Cooperaton Intervention Series). Geneva, Switzerland. Retrieved from http://www.ilo.org/wcmsp5/groups/public/---ed_emp/---emp_ent/---ifp_seed/documents/genericdocument/wcms_159435.pdf

Mel *et al.* (2014) found that entrepreneurship training has an impact on businesses formed after the training while training has no impact on running a business that was formed before receiving training. Furthermore, the heterogeneity of the type of businesses receiving entrepreneurship trainings makes it difficult to find significant results. The unique circumstances of our experiment presented an opportunity to control for these two factors: all individuals received training prior to starting their survivalist business (collecting bones) and all participants were working within the same sector. In our experiment, there is a treatment group in which individuals were given a seven-hour training in addition to a permit to collect bones and a control group in which participants received only a permit to collect bones.

3.3.3 The entrepreneurship training

We collaborated with an experienced trainer-of-trainers specializing in teaching ILO's SIYB training to develop a seven-hour entrepreneurship training using exercises from taken from the work participants would be doing in bone collecting (see Appendix B for training outline). While our training is shorter than most programs, the length of trainings in previous evaluation have ranged from 6 hours to 20+ hours (McKenzie & Woodruff, 2013). Our training program contained four modules: general overview of entrepreneurship; how to become an entrepreneur; organizing an enterprise; operating an enterprise. The training consisted of a PowerPoint presentation by the trainer, which was periodically paused so that trainees could break into small groups for active-learning exercises. The information provided and the skills learned during the training were meant to be sufficiently broad so as to be generally useful in starting any new business. The specific exercises pertaining to bone collecting were meant to directly aid problem solving in collecting bones. For example, we expected arbitrage to be commonplace in the trial. As part of a training exercise, the participants were asked to calculate the costs of purchasing and reselling bones (transport, payout to non-participant collectors/businesses) and determine how many bones they would have to collect in order to generate an income commensurate with their previous work.

Most entrepreneurship training experiments allow for a follow-up survey at least four months after the administration of the training and ideally, would have multiple follow-up surveys with the last taking place two years after the training was completed (de Mel, McKenzie, & Woodruff, 2014). The time between the baseline and follow up survey should be long enough for business both to start and to fail (McKenzie & Woodruff, 2013). The short time frame of our experiment (six weeks) largely precludes the formation of businesses outside of bone collecting. As a consequence, we are relying on the opportunity of bone collecting being sufficiently desirable so as to draw permit holders from their previous, alternative income sources. We do not expect to detect significant numbers of new business forming outside of bone collection related activities.

3.4 Research implementation and data collection

3.4.1 Generating and re-generating a sample

Our initial sample population was drawn from the rolls of the Jimma Town Small- and Micro-Enterprise Agency (JTSMEA). JTSMEA is the office of the Jimma municipal government responsible for finding work for unemployed individuals by organizing small- and microenterprises. The agency committed to contacting 200 individuals, sending them in groups of 30 during each day of the baseline. The first group sent by the agency, however, was organized into a micro-enterprise, which in hindsight should not have been such a surprise.

The group tried to negotiate the per kilogram price for bone residues. Our initial intent of the study was to start buying bone residues at low prices (.5 ETB or ~0.02 USD) and incrementally raise prices to boost collection activities and bone intake at the collection site[16]. The group of individuals was asking for 5 ETB per kilogram. When we told the group of participants from JTSMEA that we were not able to accommodate their request, they refused to participate in the experiment.

Following the calamitous first day, we spoke with the leadership at JTSMEA and asked if they would be able continue providing participants without organizing them into micro-enterprises. The agency was unable to accommodate the request because their mandate from the municipality was to organize individuals into micro-enterprises, and we were forced to find a new group of participants for the trial.

In order to quickly identify new participants, we went to six the *kebele* offices (*kebeles* are the smallest iteration of municipal government) and requested that they identify 25 individuals to participate in our experiment[17]. After weeks of near daily visits to each *kebele* office, we were able to generate a sample of 95 individuals.

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[16] By changing the payout price, we had hoped to generate data that would allow us to calculate price-elasticity of supply and subsequently, the supply function for bone residues. More is available in chapter 4 section 3.

[17] Working directly with kebele offices can be extremely difficult. The offices, in practice, are run in a very top-down fashion, such that only the office head holds any real authority. The heads of the *kebele* offices are absent for

It was quite visible that the first group of participants from JTSMEA was from a middle class background: their clothes were new and un-torn; their personal hygiene was very good; they spoke very clear Amharic and had a high level of educational achievement. Middle class individuals were not part of the target population for the intervention. The second group of participants identified by the *kebele* offices, however, visibly poor: their clothes dirty and torn; their personal hygiene was poor; many smelled of drink, spat masticated sugar-cane onto the floor or chewed *khat*[18] while waiting to be interviewed. Unlike the group from JTSMEA, the new participants from the *kebele* offices were eager for an opportunity to work. While the work of identifying new participants was immensely difficult and exhausting, the new group represented a much more realistic sample for the work of collecting bones.

Due to our experience with the first group of participants from JTSMEA that demanded 5 ETB for each kilogram of bone, our starting payout price was 2 ETB (~0.10 USD) per kilogram of animal bone. During baseline interviews, there were no individuals that argued that the 2 ETB price was too low. In fact, a number of participants told us during the baseline survey that they would be willing to collect at any price, even .5 ETB (~0.02 USD) per kilogram. This tells us that the participants in the initial group from JTSMEA were likely over-qualified for the bone collecting or had other, better means of generating an income.

many days of the week and, since there is no email in these offices and the administrators demand in-person conversations, it can take weeks or even months to initiate contact with right people at each office.

[18] *Khat* or *Chaat* is stimulating leaf chewed throughout East Africa and the Arabian Peninsula whose active ingredients are categorized as a schedule I drug in the United States.

3.4.2 Baseline interview

The baseline interviews were conducted January 11-14, 2016, in the JTSMEA building. Each day approximately 20 new participants were integrated into the project as a group[19]. After the head enumerator explained the responsibilities and benefits of participating in the project, an enumerator sat with each participant to sign consent forms, give a short safety training, conduct baseline interview, present the individuals with a unique collecting permit and assign them to a treatment.

The baseline interview consisted of seven sections: I- Participant History; II- Household Status; III- Work and Income; IV- Alternative Income (such as government assistance); V- previous business experience; VI- Entrepreneurial Mindset and Perceptions of Bone Collecting; VII- Business Knowledge. While the most widely accepted and valid method for measuring income is through an assessment of the individual's assets (de Mel, McKenzie, & Woodruff, 2009), our short, out-of-the house interviews did not allow for a reliable accounting of household assets. Instead we took the multi-step methodology used in Karlan and Valdivia (2011)[20] as a measure of income and used other instruments for well being, such as meat consumption and discretionary spending on items like clothing, home improvements and electronic.

I was present at the majority of the baseline activities, and from my observations, it was obvious that the enumerators were largely unfamiliar with the survey materials. As mentioned above, we used a multi-step method for eliciting income of participants. This method consisted of asking

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[19] Each day, a number of children tried to lie about their age and enroll into the project. Since they could not present an identification proving their age, they asked to leave the premises.

[20] Karlan, D., & Valdivia, M. (2011). Teaching entrepreneurship: impact of business training on microfinance clients and institutions. *Review of Economics and Statistics*, *93*(2), 510–527.

individuals the number of weeks they work a month, the number of days they work a week, the manner and frequency that they were paid and lastly, the amount of the last payment received. During routine data checks, unusual numbers were appearing in the final income calculation. Individuals working as day laborers[21], claimed to have been paid more than the president of Jimma University. Other participants reported zero sources of income. These answers, among other dubious responses, were incorrect, and enumerators were asked to reach out to participants to get the correct responses. Reconnecting with participants was difficult because enumerators had not collected useable contact information for many individuals, forcing Enumerators to seek a number of participants at their home address, but it is not clear that enumerators were being honest when they said the task was completed.

To check if enumerators had an influence on income, we ran an OLS linear regression for income with dummy variables for each enumerator in Stata. A joint F-test of the null hypothesis that the combined coefficients for enumerators were zero yielded an F-statistic of 3.68, which was significant at the 1% level[22]. This indicates that there is an enumerator effect on the baseline estimates for participants' income.

A weeklong enumerator training and field-testing of the survey had been worked into the budget, but it appears that these activities were not completed. Enumerators, while holding master's degrees in agricultural economics and related fields for which their thesis and classes were completed in English, were unable to understand or speak English at any more than the

[21] Jimma University, our partner organization, pays day laborers 15 ETB per day but the private sector rate is closer to 50 ETB

[22] Two enumerators combined to interview only 8 individuals. If those observations are dropped from the sample and the same test is performed, the enumerator effect becomes even stronger.

most basic level. This language barrier forced us to delegate the task of training to academics from Jimma, which was an obvious mistake. In future research in Jimma and the surrounding communities, it may be better to budget for outside expertise to conduct surveys. While more expensive, it is not clear that local institutions have sufficient number of personnel with the experience and skills to run this kind of experiment without significant outside oversight.

The final section of the interview, business knowledge, was administered as a quiz consisting of ten questions. A similar, though distinct set of questions was administered during the follow-up interview. If the training were improving business knowledge, we would expect to see an increase in the number of correct answers among the treatment group (those receiving training), whereas we would expect the score of the control group (those receiving a collection permit but no training) to remain more or less constant. Enumerators performing the baseline survey also had a significant effect on participant responses in the business quiz section of the survey.

Prior to the baseline interviews, each permit number was randomly assigned, via simple randomization, to either the control or training groups. If an individual received a permit number that was assigned to the training group, the enumerator presented the participant with a training voucher. The voucher, which had the date and time of the training, was redeemable for 75ETB (3.56 USD) and a free lunch if the individual completed the seven-hour training. This financial incentive is common for boosting attendance in entrepreneurship training experiments, and there is evidence that they are effective (McKenzie & Woodruff, 2013).

Despite an effort to establish a clear protocol for enumerators, the random assignment of participants to the treatment and control groups was not performed properly. It appears that a number of enumerators assigned participants to the treatment group without consulting the randomization procedure. As a consequence, a total of 56 (59%) participants were given a voucher to attend training, while only 39 (41%) were assigned to the control group. While there were problems during the assignment, no assignment bias was identified in the data[23] (Bruhn & McKenzie, 2009).

While it was easy to identify the mistakes with income and group assignment mentioned above, there are likely many more errors in the data collection that are not so blatantly manifest. These mistakes may lead to errors in analysis; our job in describing the data, however, is not only to identify potential errors, but also to use our time on the ground and myriad conversations with participants and community members to identify the most useful and reliable information coming out of the experiment.

3.4.3 Participant characteristics and pre-trial perceptions of bone collecting

The majority of participants were Muslim (61%) with the remaining being either Pentecostal or Ethiopian Orthodox Christians. The sample was composed almost entirely of poor urban young people, with a mean age of 23.59 years (the oldest participant was 40 years old). Despite the problems we encountered with the baseline enumerators, income among participants was in line

[23] An ordinary least squares regression with group assignment on the left-hand side and education, age, religion and income as regressors had no significant variables at even the $p>.25$ significance level.

with expectations. The average monthly income for an individual from the sample is 994 ETB[24] (1.60 USD per day), which is very close to the per capita gross national income of 1.62 USD per day (World Bank, 2016). The most common job among the participants was a day laborer (an individual hired on a per-job basis for what is typically informal employment). With the sample, 30% worked as a day laborer in one form or another. Other common jobs among participants included carpenter (15%), construction (6%) and shoeshine (6%). The average individual worked 17 days and earned 59 ETB per day of work in the month prior to the baseline survey. These earnings are commensurate with our understanding of the expected daily earnings for unskilled labor in Jimma[25].

The overall perception of bone collecting was positive, with a vast majority of participants stating that bone collecting was a good opportunity (96%) with which they could support their family (81%). A vast majority expected bone collecting to be their primary source of income during the experiment (95%). A significant number of participants felt that collecting was either bad for their health or would affect their social standing (26% and 19%, respectively). The majority of those who felt their health orsocial standing would be negatively affected by collecting also stated that bone collecting was a good opportunity.

This contradiction could mean a couple of things. One possibility is that these individuals are desperate for work and are willing to compromise their health to find a way to generate income. The other possibility is that participants are responding positively to questions about bone

[24] Exchange rate based on december 2015 ETB to USD from US treasury department: https://www.fiscal.treasury.gov/fsreports/rpt/treasRptRateExch/itin-12-31-2015.pdf

[25] As stated earlier, the publicly understood wage for a day laborer in Jimma is 50 ETB. Day laborers in our study earned an average of 56.62 ETB.

collecting in the hope of securing additional benefits or else ensure that their response does not compromise the benefits that they were already offered.

Table 3.1 Baseline Summary

Category	Variable	Mean	Std. dev.
Demographic	Female (share of total)	0.09	0.29
	Age	23.59	5.86
	Education	6.42	3.01
	From rural community	0.43	0.52
	Muslim	0.61	0.49
	Meat consumption (meals per week)	1.47	1.03
Economic	Monthly income (ETB)	993.91	816.70
	Earnings per day of work	58.96	36.96
	All savings (ETB)	698.33	1661.95
Perceptions of bone collecting	Collecting will be primary income	0.95	0.22
	Good opportunity	0.96	0.20
	Can support myself/family	0.81	0.39
	Expects ridicule while collecting	0.19	0.39
	Collecting is bad for health	0.26	0.44
Business quiz	Number of correct answers (out of 10)	5.68	1.35
	Total participants (N)	95	--

In the baseline survey 95% of participants expected bone collecting to be their primary source of income, but only 35% expected to spend at least 30 hours per week collecting bones. In the month prior to the baseline experiment, participants worked an average of 35.41 hours per week.

Participants may have thought that they would not have to work as many hours to generate the same income as their previous work, which would explain why collecting was perceived as good opportunity.

3.4.4 Training uptake

There were two separate training sessions taking place on January 21, 2016 and January 22, 2016 with 23 and 25 individuals attending each day, respectively. The attendance rate for those receiving training vouchers was 81%, with two individuals not invited to training attending the training activities. This attendance rate is higher than the majority of entrepreneurship training experiments (McKenzie & Woodruff, 2013). The high attendance, in the face of so much disorder during the baseline survey indicates that the voucher given to invitees, which carried both a financial incentive and a written reminder of the training time and date, is a good method to boost attendance.

The total cost of designing the training was ~400 USD. If we disregard the initial cost creating the training modules, the total cost of administering the training was ~580 USD and 12.08 USD per participant. Most entrepreneurship trainings are quite expensive, with other training programs in Africa costing 60-400 USD per participant, though these other courses were considerably longer than our training program (Berge, Bjorvatn, Juniwaty, & Tungodden, 2012; Glaub, Frese, Gramberg, Friedrich, & Solomon, 2012; Mano et al., 2012). Cost is an important consideration when analyzing the impact of a training program: 60 USD is the approximate monthly salary of a day laborer in Jimma.

Table 3.2 Breakdown of Training Costs

Item	Total Cost	Cost Per Participant
Trainer Salary	USD 246.80	USD 5.14
Projector Rental	USD 47.46	USD 0.99
Printing Voucher and Materials	USD 72.61	USD 1.51
Particpant Lunch	USD 42.24	USD 0.88
Partipation Fee	USD 170.88	USD 3.56
Site Rental	USD 0.00	USD 0.00
Total	**USD 579.99**	**USD 12.08**

The benefits of having received the training should be greater than the cost of providing it. We found that per participant could have been significantly reduced by increasing the number of participants attending each day of training. The training took place inside the JTSMEA building, free-of-charge. There are a number of private entities, such as hotels, that would have been able to provide an adequate space to conduct the training if the JTSMEA had not offered their facilities. That being said, there is no shortage of public institutions willing to offer their facilities for free for training activities. Public institutions in Jimma, though slow in completing certain tasks, are eager to connect their constituents with benefits and opportunities. Future programs would do well to leverage this sentiment to find facilities with little to no cost to reduce the costs of implementing their programs.

Figure 3.2 Group exercise during first day of entrepreneurship training

Figure 3.3 Trainer-of-trainers giving powerpoint during entrepreneurship training

3.4.5 Bone Collection

The original collection site was a 3x3 meter, government-owned *suuk* (small storefront) in Kochi, a middle-class neighborhood in Jimma's *kebele* 5. This site opened on January 15, after all participants had completed the baseline interview but before the training had been completed. A line of participants with tattered nylon sacks of bones were waiting near the collection site when it opened at 9:00 am. Before the collection site closed for lunch, 17 individuals had sold a total of 1265 kg of bones. The average payout was 148.82 ETB, nearly three times greater than average daily wage for participants in our experiment. One individual sold 662 ETB (331 kg) worth of bones on that same day[26]. The intake was so much larger than we had expected, that the collection site ran out of money to pay collectors and shut down the same afternoon.

The site in Kochi never reopened. There were two reasons that we closed the site. First, the participants more-or-less constantly fought while waiting in line to sell bones and made a scandalous amount of noise in an otherwise safe and tranquil neighborhood. Figure 4 shows the location of the *suuk* we used as our initial storefront for purchasing bones. It is not visible in the photograph, a line of upper middle class family homes sit across the street from the original collection site.

The children of the neighborhood use the street as a *de facto* playground. We felt bringing dozens of squabbling, often intoxicated men hauling sacks of animal bones to a rich neighborhood would put at risk the public image of our research partners and subject

[26] The individual told us that he had gone out with his family to collect the bones, so it is reasonable to assume that he was not receiving 100% of the payout.

Figure 3.4 Children play *igirkwas* (soccer) in front of the original collection site

neighborhood children to potentially hazardous biological materials. Second, the 3x3 structure was too small: it had filled in after only 3 hours of operation. A much large facility was required for the trials.

The second bone-purchasing site was located in an area called *bishishe* (literally translating as "dump"), which is located behind the wholesale vegetable market in a non-residential section of downtown Jimma. The new facility was composed of three 3x5 rooms and cost 33% less than the original site. Individuals were alerted to the change of site by telephone and by signs posted at the original collection location. A number of participants, however, were never contacted. Baseline enumerators had not collected contact information for many participants. Those participants whose contact information was not gathered may have had trouble locating the purchasing site, thus preventing them selling bone residues.

Collection activities recommenced on January 25, 2016, after the completion of the entrepreneurship training. Upon opening the new site, an 80kg daily limit was imposed on the number of bones participants could sell to the collection site, a change forced by limited resources for purchasing bones and logistical concerns associated with storing and transporting bone residues. There are significant consequences to imposing a limit on the quantity of bones participants are permitted to sell at the collection site. One research question of the trial pertains to the maximum quantity of bones that could be collected from within the municipality. Production of bone char fertilizer benefits from economies of scale (see Chapter 4) and the limit on the quantity of bones that can be sold ensures that we do not achieve maximum collection potential.

Along another dimension, we were told that some participants had paid others to collect bones and had amassed enough residues to fill a flatbed truck. These individuals were leveraging their permit to become the middlemen we had envisioned at the start of the trial. Their ingenuity and entrepreneurialism, however, will not be reflected in the collection data because they would not be able to sell their "truckloads" of bone residues. Our intention of providing training was to create entrepreneurs, but the imposition of the daily limit prevented entrepreneurial behavior, such as the example above, from being reflected in the bone collection data. As a consequence, the chance of observing an impact of training on income among collectors is greatly reduced.

During the first four days collection, an average of 2687 kg of bone residues were purchased per day with the average transaction worth 164 ETB. During the first week, the average number of bones sold per transaction was greater than the maximum allotment of 80kg per day. Due to

Figure 3.5 Collectors wait to sell bones in *bishishe*

Figure 3.6 Bones sit at the collection site awaiting transport to the storage facility

negligence on the part of research personnel at the collection site, a number of participants were able to sell bones more than once during any given day. Despite efforts to address the problem, this issue persisted throughout collection activities[27]. During the second week of collecting, the payout price was lowered to 1.25 ETB per kilogram. After the price change, collection continued for 4 days with an average of 2095 kg per day and the average transaction equal to 143.50 ETB.

By the end of the experiment, 77% of the sample made at least one sale to the researchers and 51% of participants sold bones to researchers more than once. Individuals attending the training were more likely execute at least one sale than those individuals not attending training (89.58% and 63.83%, respectively) and were nearly twice as likely to make multiple sales of bone residues to the collection site. The average quantity of bones sold per participant was 205.97 kg. Those attending training sold 73% more bone residues (260.21 kg) during collection activities than individuals that did not attend training (150.60 kg).

Once collected, the bones were transferred to an enclosed storage site on unused land owned by Jimma University. Shortly after the first delivery of bones to the storage site, some university officials began complaining to members of our research team, expressing fear that the bone storage would attract hyenas, endangering members of the university community and that the unpleasant odors would draw complaints from the surrounding community. These concerns forced collection activities to cease for a second time, after just 8 days of collecting.

[27] It is not clear if the issue was miscommunication, embezzlement or favoritism on the part of the employees. There are some cases in which collectors were allowed to sell more than 80kg of bones in a day because the previous day they had brought bones to the collection site and were unable to make a sale (collection site had run out of money etc.)

Table 3.3 Daily collection totals

Date	Payout (ETB / kg)	Number of Transactions	Total kg Collected	Average Transaction (ETB)
January 14[1]	ETB 2.00	17	1265	ETB 148.82
January 25	ETB 2.00	28	2192	ETB 156.57
January 26	ETB 2.00	17	1434	ETB 168.71
January 27	ETB 2.00	30	2422	ETB 161.47
January 28	ETB 2.00	56	4700	ETB 167.86
January 30	ETB 1.25	17	2509	ETB 184.49
February 1	ETB 1.25	20	2240	ETB 140.00
February 2	ETB 1.25	14	1753	ETB 156.52
February 3	ETB 1.25	22	1878	ETB 106.70
Total	1.69 ETB[2]	221	20393	ETB 154.57

[1]January 14 is the only day that collection took place in the Kochi neighborhood. Since collection activities were short-lived and this day took place before the training, the collection data for this day will not be used in analysis of the training; [2] This is the mean payout price for the collection experiment

After three weeks of continued engagement with university officials, it became clear that their concerns about safety and the community's perception of bone storage on university land were premature and Jimma University gave permission to restart collection activities. Guards stationed near the bone storage site reported that there was no increase in hyena activity and that they were unable to notice unpleasant odors emanating from the storage site. Most of the bones sold by collectors were old, desiccated and any odor-producing soft tissue had long since rotted away. Despite the university's permission to continue collecting activities, we decided to permanently close the collection site.

The choice to stop collecting was made because the value of the information we could gather by collecting additional bone residues (with respect to new insights on bone supply and its impact on collector well being) was very low. There had been so many problems throughout the implementation of the experiment that many of the participants had likely dropped out of the program or grown wary of unfulfilled promises on the part of research personnel. It was also clear that the running the collection site and processing the costs through the Jimma University's financial system were generating a lot of extra work for the research team and burning through the research equivalent of political capital. Eventually, the remaining resources that had been marked for the collection experiment were reallocated to other areas of research where they would have a greater impact[28].

3.4.6 Follow-up Survey

Follow-up interviews were administered February 29 – March 18, 2016. A total of 79 individuals were interviewed in the follow-up survey for an attrition rate of ~17%. Individuals that attended the entrepreneurship training were overrepresented in the follow-up survey. Among participants that attended training, the attrition rate was 8.33%, whereas participants that did not attend the training had an attrition rate of 25.53%. An OLS regression of attrition with key baseline characteristics (income, education, religion and age) as regressors indicates that there is no other statistical difference between contacted and non-contacted participants (Bruhn & McKenzie, 2009). The difference likely stems from the baseline survey enumerators having failed to collect the contact information of participants. During the trainings, new contact information was collected for each participant. Our ability to contact these individuals likely contributed both to their increased participation in collection activities (alerting them to the location change of the

[28] The slow-moving and bureaucratic financial arms of both Cornell University and Jimma University and the organizations funding research make it immensely difficult to transfer money internationally. Additionally, Jimma University is particularly ill equipped for processing unusual transaction (such as payments for bone collectors). This is another reason that hiring a private third party to run research operations is an advisable investment if there are adequate resources.

collection site), and their higher representation in the follow-up survey.

New enumerators were hired to conduct the follow-up survey, but the validity of their work was once again brought into question. Unlike the baseline study, which I was able to observe and therefore, monitor as the data was generated, I was not in Ethiopia during the follow-up survey. In entering the data from the follow-up survey, responses to the business practices quiz appeared to have a repeating pattern for certain enumerators. An F-test for the joint effect of enumerators on correct answers in the business knowledge quiz yielded an F-statistic of 8.19 and significant at the 1% level[29]. In my return to Jimma after the completion of follow-up activities, I sat and spoke with a pair of enumerators. They said that during the quiz component of the survey, they helped the interviewees answer the questions; enumerators conducting the follow-up surveys did not significantly bias other sections of the survey, such as the components eliciting income, savings and attitudes towards employment collecting bones. Just as in the baseline, the enumerators were not properly trained and did not understand certain aspects of the survey.

3.5 Results and Analysis

Summarizing the results from this experiment is a very complicated task. Collection activities stopped 4 weeks prior to the follow up interview, and all questions in the follow-up survey pertaining to alternative income, i.e. non bone collecting income, were estimated using the four weeks prior to the follow-up survey. This makes it difficult to determine whether participants had used bone collecting as their primary source of income or continued in their normal job,

[29] The R^2 for the regression was 0.3595, which suggests that more than a third of variation in business score quiz was dependent upon the enumerator.

treating collection as an alternative income source. Additionally, collection activities were crippled by constant problems (stoppages, the collection site moving or running out of cash to pay collectors, *etc*.), and what was originally meant to be a semi long-term employment opportunity was rendered a tumultuous and inconsistent 2-week opportunity. Due to these problems, it is not entirely clear whether individuals that did not sell any bone residues were actively collecting but unable to locate the collection site or simply did not want collect bones. The shortened period has the greatest impact in our ability to analyze the effect of the entrepreneurship training component of the experiment, since much of the content was aimed at improving productivity and income within the context of bone collecting. In the following section, we will present our findings, assess their validity and determine their implications for a bone residue supply chain

3.5.1 Who collected bone residues?

There is little difference, demographically, between the individuals that sold bone residues and those that did not. In an OLS regression with a binary variable for whether or not an individual made a sale to the collection site and socio-economic data[30] as independent variables, no variable was significant at even the a $p > .15$ level of significance. The statistical power of our analysis is very low, and the lack of significance for the variables baseline income and rural is likely due to the small sample size.

There were only 9 females in the sample, all but one individual sold bone residues. This suggests that both men and women can be expected to collect bones. Scavenging in other sectors in other

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[30] Regression included baseline income, education, age, Muslim and “originally from a rural area

countries can be shared or dominated by both sexes (Berner et al., 2012; Schenck & Blaauw, 2011). From personal discussions with participants, we suspected that child workers, such as *keraliou*, were participating in collection activities via arbitrage. This information was confirmed in the in the follow-up data. A total of 9% participants paid children to collect bones on their behalf. Other researchers have found that children also play an important though controversial

Table 3.4 Socio-economic characteristics of collectors and non collectors[1]

Characteristic	Collectors[2]		Non-Collectors	
	Mean	*S.D.*	*Mean*	*S.D.*
Baseline income (100s ETB)	10.45	8.77	8.24	5.58
Education	6.53	2.84	6.05	3.54
Age	23.60	6.02	23.55	5.43
Muslim	0.62	0.49	0.59	0.50
Originally from rural area	0.36	0.48	0.57	0.51

[1]The data for this table was taken for all participants, including those that did not come to the follow-up survey [2] Collectors are individuals that sold bones at least once during collection activities

role in scavenging work, representing 25-33% of the population (Benjamin, 2007; Parrot, Sotamenou, & Dia, 2009). Preventing children from collecting bones is an important consideration for efforts to collect bone residues from the waste streams and a critical area of investigation for future research.

A large number of participants said that they were actively collecting bones but never able to make a sale at the collection site. All but two participants (2 out of 79) told enumerators that they had spent time collecting bones and 40% of individuals that never made a sale to the collection site (n=16), reported that they had either invested in equipment for bone collecting or else paid someone else to collect bones on their behalf.

There is likely a difference between the proportion of individuals that claim to have spent time collecting bones and those that would have actually sold bones had the collection activities not been hindered by the myriad problems we have already discussed. That is, even had everything gone smoothly with the collection site, there would have been individuals that would start collecting bones and either find the work too difficult or else decide that they preferred their other employment before they made a sale. Some of the data supports this hypothesis. Individuals that sold bones at least once to the collection site spent 68% more time collecting than those that did not. That being said, it is likely that some individuals that collected bone residues were unable to locate the new collection site or else unable to come to the site during the short collection window.

We are not only interested in who collected bone residues, but the factors that impact productivity among those that opted to participate in bone collectoring. Using data from the baseline survey[31], we performed another OLS regression with kilograms of bone residues sold as the dependent variable and sex, age, baseline income, rural origin, and training attendance as right-hand side variables. The results can be viewed in table 5.

In the model, baseline income can be interpreted as proxy for work ethic or working rate. Most of the participants in the trial are unskilled day laborers from the informal sector, so we assume that they all have a more-or-less equivalent earning potential. Most of the participants told us in the baseline survey that they are paid on a "per job" basis, so the faster they work and the more

[31] We are able to document who sold bones and how many bones were sold without consulting the follow-up survey. In order to maximize statistical power, we will use the full baseline sample to analyze the dynamics of participant choice to work as a bone collector and their productivity (kg of bone collected). For analyzing the collection practices, we will use a sample consisting only of the individuals from the follow-up survey.

actively they search for employment, the higher their income is going to be. Using the number of hours worked would not capture work rate and therefore is not as strong an instrument for work ethic. Rural, which is participants' response to the question, "were born in a rural area", is highly

Table 3.5 Bone collection productivity regression results

Model Specification		
Variable	Coeff.	S.E.
Treatment of the Treated (TOT)		
Constant	170.15	65.70**
Training attended	98.62	36.63***
Income (100s ETB)	6.75	2.23***
Female	68.88	62.78
Education	-5.05	7.16
Rural	-134.54	43.11***
Adj. r^2	0 .2082	--
Intent to Treat (ITT)		
Constant	177.31	67.71**
Invited to Training	70.90	37.79*
Income (100s ETB)	6.65	2.28***
Female	78.78	63.91
Education	-4.62	7.32
Rural	-140.83	43.87***
Adj. r^2	0.1763	--
Sample (N)	95	

*sig. at p<0.1; **sig. at p<0.05; ***sig. at p<0.01

and negatively correlated with educational attainment (*corr*=-0.5326). Adding education to the model is meant to control for this correlation and see if there is some other effect of being from a rural or peri-urban home on collection productivity.

The results indicate that training has a large and significant impact on the number of bones an individual collected, so much so that impact of training is significant at the p>.10 significance level in the intent-to-treat model. Baseline income, our proxy for work ethic, is a highly significant predictor of collection productivity. Being born in a rural area is highly significant and negatively affects collection in a very strong way. While the effect of "rural" on collection is clear, the mechanism for as to why individuals born in rural communities collect fewer bones is not.

3.5.2 Impact of training on collection and income

There is little doubt that the entrepreneurship training significantly increased the number of bones sold. The impact of the training, however, did not create more productive collectors, but instead, increased the number of individuals that made at least one sale to the collection site. Among individuals that made at least one sale to the collection site, attending the training has no significant effect on the quantity of bones sold. Table 6, below, shows the results of same regression as the TOT model from table 3.5, but only included individuals making at least one sale to the collection site, and the impact of the training on bones collected disappears.

We previously mentioned that the contact information of the was recollected during the the training sessions. If an individual attended training, it was more likely that we would be able to contact them when the collection site changed location or when the collection site opened, which would almost certainly increase the likelihood of selling bone residues at least once. On the other hand, the training also described bone collecting as an entrepreneurial, potentially highly

Table 6. Productivity regression results among collectors only

Variable	Coeff.	S.E.
Constant	281.50	75.28***
Training attended	39.28	41.49
Income (100s ETB)	5.65	2.29**
Female	30.90	64.94
Education	-6.56	8.62
Rural	-143.44	48.59***
Adj. r^2	0.14	--
Sample (N)	95	

*sig. at p<0.1; **sig. at p<0.05; ***sig. at p<0.01

remunerative opportunity, which may have generated excitement among collectors, spurning them to take up collecting. Lastly, individuals from the training had already invested significant amounts of time learning about bone collection and bone collection strategies. Trainees may have felt some loss aversion for the opportunity costs of attending the training, and thus felt compelled to at least try selling bone residues. Unfortunately, our follow-up survey did not include a qualitative component asking why individuals chose to spend time collecting bones. Future work should include more free form answers so as to elicit an honest and spontaneous response that drives the choice to work as a bone collector.

Training did, however, significantly impact the way individuals from the training group collected bones. In an OLS linear regression for arbitrage (whether or not participants bought and resold bone residues) with the same sample and regressors as the model in table 3.6, training significantly increases the rate of arbitrage at the $p>.10$ level[32]. Arbitrage was an important component in the entrepreneurship training. In the training, participants were asked to calculate

[32] For training attended, P>|t|= 0.062 . No other variables were significant at $p>.15$ level.

costs for arbitrage and determine if they were able to generate more income from collecting directly or through reselling bones collected by others. Again the opportunity was envisioned such that permit-holding collectors would become middlemen, leveraging the economic rent generated by the exclusivity of their permit. These middlemen are important components of other scavenging industries (Tuori, 2012). Because of the limits on the amount of bones that could be sold in a day, collecting bones via arbitrage was not an optimal strategy in our experiment. In an unrestricted environment, however, acting as a middleman would produce much larger incomes than scavenging the bones directly (Tuori, 2012).

Interestingly, another component of the entrepreneurship training pertained to human resources, and in one exercise of the human resources module, the trainer led a discussion on the ethical issues surrounding the employment of children. Though trainees were more likely to employ others to collect bones on their behalf, they were less likely to employ children. Approximately, 9% of the sample (7 individuals) paid children to collect on their behalf. Among the individuals that received training and also sold bones at least one time, there were none that employed children to collect on their behalf. The rate of child labor among individuals that sold bones but did not receive training was 25%. The sample size is very small, but these findings suggest that training may be an effective means of reducing child labor within the bone residue supply chain.

Those receiving the entrepreneurship training experienced a small loss of alternative income (income not earned from collecting bones) from the baseline to the follow up survey. This drop in alternative income is could be due to the time spent collecting bones reducing employment in other sectors. Additionally, the income data for the follow-up survey could be more accurate than the baseline (enumerator bias effects), and that those individuals that collected more bones were those who were actually earning less at the start of the experiment. As we expected, the small timeframe of the experiment did not allow for the formation of a significant number of new businesses. One new business did form during the experiment: a middleman-type business reselling scrap metal. The individual had not participated in the entrepreneurship training.

The business quiz that was intended to measure the effect of the entrepreneurship training on business knowledge was improperly administered at both the baseline and follow-up surveys. It is not surprising, therefore, that the training had no impact on business knowledge. The lack of significant improvement in business score does not necessarily signify that the training did not impact business knowledge. The only factor that significantly impacted business score was the enumerator administering the survey.

3.5.3 Post-trial perceptions of bone collecting

Despite the problems with the collection site, participants continued to tell enumerators that bone collecting was a "good opportunity" (96% baseline, 84% follow-up/post-trial). While it is not absolutely clear if this opinion is based on what collection "should have been" or the opportunity they were actually given, even individuals that never made a sale at the collection center remained optimistic, with 73% feeling the bone collecting was a good opportunity. This gives some indication that participants are basing their opinion on optimism rather than their actual experience. For individuals interviewed in the follow-up survey there was a large reduction (81%

to 56%) in the number of participants that felt they could support themselves and their household with the income from bone collecting.

There were two questions on both the baseline and follow-up survey asking participants about the negative perceptions associated with bone collection. One question asked if they felt collecting was bad for their health or the health of the community while the other question was whether they would feel judged/embarrassed if their neighbors saw them collecting bones. In the baseline survey, 39% of individuals said that at least one of the two issues concerned them. In the follow-up survey, concerns about the health or social impact of collecting bones increased to 49% of respondents. Additionally, 32% of respondents reported that people made "hurtful or discouraging" comments while they were collecting bones.

The perception of negative consequences of bone collecting on the health and social standing of collectors had virtually no effect on a participants' decision to collect bones (80% v. 82% for collectors[33] and non-collectors, respectively) or on their perception of bone collecting as a good opportunity (85% v. 82% for collectors and non-collectors, respectively). This speaks to the somewhat desperate economic situation of the participants, in that they are willing to accept what they perceive as dangerous work for relatively little compensation. However, it is not clear how these negative perceptions would affect employment in the bone residue supply-chain in the long run. It may be the case that some at-risk individuals will use bone collecting as a "stop-gap" source of income and their negative feelings would eventually drive them to continue looking for alternative employment. Additional work should be done to find the determinants of entrance and exit from employment in bone collecting.

[33] Collectors, in this instance, are individuals that made at least one sale of bone residues to the collection site.

Table 3.5 Follow up summary[1]

Category	Variable	Mean	Std. dev.
Economic	Monthly income (not from collecting, ETB)[2]	8.45	9.07
	training group	7.56	7.44
	non-training group	9.57	10.80
	change from baseline	-1.52	1.14
	Bone collecting payments (ETB)	3.71	3.20
	training group	4.29	3.05
	non-training group	2.99	3.28
	Adjusted Bone collecting income[3] (ETB)	3.05	2.86
	training group	3.39	2.65
	non-training group	2.62	3.10
Post-trial collecting perceptions	Good opportunity	0.84	0.37
	Can support myself/family	0.56	0.50
	Collecting is bad for health	0.33	0.47
	Ridiculed/insulted while collecting	0.32	0.47
	Embarrassed to be seen collecting	0.30	0.46
Collection practices	Sold bones on at least one occasion	0.80	0.40
	training group	0.89	0.32
	non-training group	0.69	0.47
	Purchased bones from nonparticpants	0.51	0.50
	training group	0.64	0.49
	non-training group	0.34	0.48
	Paid children to collect bones	0.09	0.29
	training group	0.02	0.15
	non-training group	0.18	0.39
	Invested in equipment	0.30	0.46
	training group	0.30	0.46
	non-training group	0.31	0.47
Business quiz	Number of correct answers (out of 10)	6.57	1.41
	Total Participants (N)	79	--

[1] The data reported below pertains only to participants contacted in the follow-up experiment [2]The exchange rate at the time of the experiment was 20.7 ETB for 1 USD; [3]The adjusted bone collecting income attempts to account for arbitrage

3.5.4 The economic opportunity of collecting bones

As stated earlier, our collection experiment was seriously flawed. As a consequence of the limit imposed on the number of kg collected per day and the short period that the collection site was operational, generating a valid estimation for income of a bone collector outside the context of our experiment is very difficult. Furthermore, bone collecting activities and follow-up questions on alternative income generation (income generated from activities not related to bone collecting) did not coincide, so we cannot even know with certainty if individuals were treating bone collecting as their primary source of income or as a supplementary income source. That being said, there were still a number of useful insights that came out of the experiment.

The income generated from bone collecting can be measured in two ways. Using only data from individuals contacted for the follow-up survey, the average total payout (total payments for bone residues) was 371.10 ETB, which increases to 465.35 ETB if the individual made at least one sale to collectors. This first estimate, however, does not account for arbitrage (non-collectors selling bone residues to permit holding collectors for resale to collection site). In the follow-up survey, we attempted to account for arbitrage by asking participants if they had purchased bones from other individuals for resale. If they responded “yes” we then asked how much they paid those individuals and what proportion of the bones they sold were purchased from others. Accounting for these costs, the adjusted average total payout was 305.14 ETB, which increases to 382.64 ETB among individuals making at least one sale to collectors.

The total payout amounts in the above paragraph were made during 8 days of collection. A fully functioning collection site would be open 5 days per week or ~20 days per month. If we extrapolate from the initial 8 days for a 20-day month, the average collector's monthly income (those that made at least 1 sale) would be 1163.38 ETB if we do not adjust for arbitrage payments and 956.60 ETB if we do adjust for arbitrage payments. The average baseline income for these participants was 996.66 ETB.

There are two problems with applying the above estimates for monthly income among bone collectors to a "real-world" bone residue supply chain. The first is that the daily limit on the quantity of bones individuals could sell to the collection site. We cannot know how many bones would have been sold if the restriction were not in place. Those individuals that leveraged the economic rent of their permit to collect more bones were unable to sell in the quantities they had collected. Without this restriction, the quantities of bone residues sold per day would undoubtedly rise significantly and, all else equal, the income of collectors would also increase. The second problem pertains to the price paid for each kilogram of bone residues. Collectors were able to purchase bones from individuals without permits for prices as low as .25 ETB (the average price paid for residues by participants was closer to 1 ETB). If we assume that the number of bones collected is elastic, a rational fertilizer producer is going to identify the per kilogram price for bone that maximizes profit. While the maximization of profit for a fertilizer producer is discussed in detail in Chapter 4, the fact that participants were buying bones at prices well below 1.25 ETB indicates that the price at which individuals are willing to collect bone residues is lower than our experiment suggests. The lower price would undoubtedly affect collector income.

It is not clear to what extent individuals were sacrificing time from their initial job (the job they held at baseline) to work as a collector, but there does appear to be an inverse relationship between the quantity of bones sold by an individual (a proxy for the time they spent collecting) and the alternative income they generated. A OLS linear regression of the change in alternative income from baseline to follow-up survey with only kilograms collected on the right-hand side is significant at the $p > .05$ level[34]. For each kilogram collected, there was a corresponding 1.6 ETB drop in alternative income.

The data for alternative income was derived from a 4-week period that did not coincide with the collection site being open, however, it would hold that participants continued collecting after the closure of the collection site in the expectation that it would open again in the near future. This finding suggests that there is a trade-off: the time participants spend collecting bones was time that they were not able to work in alternative employment, resulting in a decrease of alternative income.

3.6 Collection trial results summary

At first glance, it may not seem like issuing permits and offering trainings is the most cost-effective way to start aggregating bone residues. There may be, however, real benefits of using similar methods in a private-sector setting. Firstly, the training significantly increased the quantity of bones collected and reduced the impact of collection activities on vulnerable populations, such as children. The initial investment, ~12 USD per participant, ensures that there will be a significant quantity of bones collected from the first day the collection site opens. The

[34] Regression results: coefficient (kg collected): -1.645; Standard Error: .6726; $P > |t| = .017$

issuing of permits, a physical reminder of an income opportunity, may also spearhead collection activities. Despite significant obstacles during the implementation of the collection experiment, we were able to collect an average of 2391 kg of bone residues per day at an average price of 1.69 ETB per kg ($0.08 USD) over an 8-day collection period. That is an extremely fast extraction for resources whose supply-chain infrastructure, only a week before, was non-existent. We conclude that the income generated by bone collectors is likely commensurate with alternative forms of income for individuals with limited human capital, even as the prices paid for bone residues is low enough to support an economically viable, local bone char fertilizer industry. If collection activities were to continue for an entire year, payout to collectors from our experiment would total $70,000 USD, which is enough income to support 120 individuals at the Ethiopian average income of $590 USD per year.

Our experience suggests that any entity seeking to collect bones from within a municipality in Ethiopia must do so with great sensitivity to public safety and public perception. If scavengers begin exhuming graves and storing potentially hazardous waste in inappropriate areas (we had no evidence that such activities took place in our trial), it is unlikely that a municipality will allow bone collection activities to continue. If the collection bone residues down-stream of abattoirs were not permitted, the rationale for a bone char fertilizer industry (that there are large quantities of bone residues spread across Ethiopia that are available for use in bone char fertilizer production) would be put at risk. The issuing of permits, which creates a semi-formal work force, allows for, among other things, accountability, monitoring, decentralization and participation. This kind of formalization of waste collector is an important component of good governance and has been successful in other municipalities of Ethiopia (Bjerkli, 2013)

Entrepreneurship training did not improve participant income. Furthermore, the training did not increase the total number of bone residues sold among participants that made at least one sale to the collection site. The training did, however, increase the probability that an individual would sell bone residues on at least one occasion and increased collecting practices, such as purchasing and reselling residues, which outside the context of our experiment, would generate higher earnings. Lastly, it appears that including a module on the ethics of child labor in a training program is an effective means of reducing child labor in scavenging, which is considered one of the “worst forms of child labor”.

Chapter 4. Cost-analysis and profit maximization of bone char fertilizer production.

In conducting the collection experiment described in Chapter 3, we were able to confirm that a positive price shock for bone residues would mobilize a large labor force of predominantly urban and peri-urban poor peoples. Now we must determine if the number of bones collected during the trial would be sufficiently large to support a viable bone char fertilizer production facility. The goal of this chapter is to determine the costs of producing bone char using data gathered from the collection experiment and other reliable sources where data is not available. Once the costs of producing bone char are properly accounted for, we will use our findings to generate and maximize a production function for a hypothetical bone char fertilizer producer.

4.1 Points of cost accumulation

There are four areas of cost accumulation for bone char fertilizer production: bone collecting (acquisition of principal factor of production), converting raw bone residues into bone char (production), post-production, and distribution. In the following section, we present three scenarios for the accumulation of costs in each area: a low cost scenario, a high cost scenario and an intermediate scenario. The low cost scenario is an optimistic, though realistic, scenario in which costs are minimized from collection to distribution. The high cost scenario is based on data from an admittedly flawed collection experiment and pessimistic views of the costs in other areas, such as production and post-production. The intermediate scenario is simply the average of the low-cost and high-cost scenarios.

4.1.1 Securing Supply of Bone Residues

The act of collecting bones, which represents 42-45% of the final cost of producing bone char for the scenarios specified in table 4.1, is the single largest expense of producing bone char fertilizer. The costs include the rental of a collection site and the labor to run the collection site, the amount paid to collectors (total payout) for the bones they collected, and the costs of transporting the bone residues to the production facility.

The variation in the cost of collecting bones is generated by the quantities and price paid per kilogram in different collection scenarios. The costs of site rental, labor and transporting bone are fixed costs that are held constant across all three cost scenarios. For the high-cost scenario in table 4.1, the quantity and price for bones is equal to the daily average, 2391 kg per day, and the average per kilogram price paid, 1.67 ETB, from the collection experiment in Chapter 3. In the low-cost scenario, the daily quantity of bones collected is equal to the daily quantities of bones entering the waste stream in Jimma, 4136 kg (see section 3.2 for explanation) and the approximate price at which collectors were purchasing bone from non-participants for resale during the collection experiment, 1.00 ETB. The result is that in the high-cost scenario, bone collection activities are 45% of the final cost of delivering bone char to farmers, while it is only 42% of the costs of the low cost scenario.

Table. 4.1 Cost-analysis of bone char fertilizer production

	Scenario 1 (Low Cost)	Scenario 2 (high cost)	Scenario 3 (intermediate)
Securing Supply of Bone Residues.			
1 Collection Site Rental Costs	1000	1000	1000
2 Collection Site Monthly Labor	7200	7200	7200
3 Bone Residue (Payout/month)	124080	119789	121935
Bones Residues (payout/kg)	1.00	1.67	1.34
Bones Collected (Kg/month)	124080	71730	97905
4 Bone transport to Production/Processing Site	8000	8000	8000
Total Cost of Bone Residue Collection	140280	135989	138135
Pyrolysis (converting bone meal to bone char)			
5 Processing Site Rental Costs	2500	2500	2500
6 Labor at Pyrolysis site	9000	9000	9000
7 Wood Costs per month	97770	102606	100188
Wood Cost (per m^3)	350	350	350
Wood per Kg Bone Char Produced (m^3)	0.0023	0.0041	0.0032
Total Bone Char Fertilizer Produced (kg)	89338	51646	70492
Pyrolysis Percent Yield (Y_{pz})	72.00%	72.00%	72.00%
Bone Residue Input	124080	71730	97905
Total Cost of Pyrolysis	109270	114106	111688
Post-Production And Distribution			
8 Monthly Granulating Cost	18883	16638	17761
Granulating Cost Per kg	0.12	0.17	0.14
Binder (cost per kg finished pellet)	0.06	0.08	0.07
Drying (cost per kg finished pellet)	0.05	0.07	0.06
Binder (cost per kg finished pellet)	0.02	0.02	0.02
Technicians	8000	8000	8000
Percent Loss during Processing	0.00%	0.00%	0.00%
9 Cost Bagging, Transport, Distribution per Month	64323	37185	50754
Cost Bagging, Transport, Distribution per kg	0.72	0.72	0.72
Total Cost Post-Production and Distribution	83206	53823	68515
Fixed Costs	35700	35700	35700
Variable Costs per kg TSP Equivalent with P_b	4.75	7.58	5.79
Variable Costs per kg TSP Equivalent. $C_{proc.}$	2.70	3.98	3.17
Variable Costs per DAP equivalent, with P_b	8.38	11.11	9.38
Variable Costs per DAP equivalent, $C_{proc.}$	6.35	7.72	6.85
Total Cost of Bone Char Production	332756	303918	318337
Total Output (Bone Char kg/month)	89338	51646	70492
Farm-gate Price For Bone Char Fertilizer (ETB/kg)	**ETB 3.72**	**ETB 5.88**	**ETB 4.80**
Farm-gate Price per TSP Equivalent	**ETB 5.44**	**ETB 8.59**	**ETB 7.01**
Farm-gate Price For DAP equivalent	**ETB 8.96**	**ETB 12.13**	**ETB 10.54**

4.1.2 Costs of converting bone residues into bone char

The costs of converting bone residues into bone char include production site rental, labor, and fuel for pyrolysis. Capital depreciation costs are not included in this analysis. As such, processing costs are equal to 33% of costs in the low-cost scenario and 38% of cost in the high cost scenario. There are two aspects of converting bone residues into bone char that requires additional explanation. The first is the cost of fuel that heats the pyrolysis kiln. In order to get the estimate of wood costs, we produced various batches of bone char and measured mass of wood used during pyrolysis[35]. The mass of wood used had to be converted to volume (Krajnc, 2015; Lindblad, Äijälä, & Koistinen, 2010). Most of the firewood available in Jimma is uncured eucalyptus of relative poor quality, so we used intermediate value for the mass to volume ratio (kg/m^3) of small diameter beech wood, 497.5 kg/m^3, which has a similar density to eucalyptus for the conversion (Lindblad et al., 2010). Wood costs in Jimma are 350 ETB/m^3 (Dr. Venkata Rammaya , Professor Jimma University, personal communication, January, 2016). The most efficient run of the kiln was used in the low cost scenario, whereas the least efficient run of the kiln was used in the high cost scenario[36]. Lastly, moisture and organic compounds are volatilized during pyrolysis, causing the bones to lose a significant amount of mass. The percent yield (proportion of initial mass remaining after pyrolysis) depends upon the temperature and time of pyrolysis. Yield can vary from 54% to 90% (Zwetsloot et al., 2015). The consequence is that one

[35] A locally built, single chamber, iron batch kiln with a base measuring 1x1.5 meters with brick housing was used to collect the data

[36] High-cost scenario- bone meal: 30 kg; wood fuel: 61 kg; max temp: 562 *C; time above 500 *C: min. 60 minutes
Low-cost scenario- bone meal: 44.24 kg; wood fuel: 49.55 kg; max temp: 523 *C; time above 500 *C: min. 20 minutes

kilogram of bone char, requires 1.1 - 1.85 kg of bone residues depending on the yield[37]. We used the intermediate value of 72% yield for both the low-cost and the high cost scenarios.

4.1.3 Cost of post-production and distribution

The costs of post-production and distribution represent 25% and 18% of costs in the low-cost and high-cost scenarios, respectively. Post-production consists of converting powdered bone char into granules[38] and bagging the finished product. The cost of distribution, which in Ethiopia is a rather complex process of cost buildups, includes anything from transport costs to profit margins of primary cooperatives (Rashid et al., 2013).

The costs for granulation were taken from a report by Mars Mineral, a private company specializing in industrial scale pelletizing equipment (Albert & Langford, 1991). While we are confident that all the necessary equipment for creating granules could be manufactured in local machine shops, an imported pelletizer capable of granulating ~3500 kg per day[39] would cost $30,500 USD (www.marsmineral.com). The costs for transport and distribution are taken from an analysis of fertilizer cost buildups in Ethiopia by Rashid, Minot & Ayele (2013).

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[37] This is one reason that the cost of collecting is the largest single cost of producing and distributing bone char: it is not a 1:1 ratio.
[38] A detailed explanation of the granulation process can be found in the essay titled "Granulation of Bone Char Fertilizer: An Evaluation of Process Parameters and Their Effect on Granule Strength", APPENDIX C.
[39] The low-cost scenario and high-cost scenario would require pelletizing equipment capable of processing ~3,000 and 1,300 kg per day, the high-cost

4.2 Comparing the cost of bone char to imported alternatives

There are currently no sole-nutrient P fertilizers that are commercially available in Ethiopia (Rashid et al., 2013). Until recently, Diammonium Phosphate, DAP, was the only widely available phosphorus fertilizer. The Ethiopian government has started building fertilizer blending facilities tasked with creating custom blends of fertilizers, such as NPS (Nitrogen, Phosphorus and Sulfur) to address the specific nutrient deficiencies for every major agricultural region of the country (ATA, 2014). The principal input for the phosphorus in these blends will be triple superphosphate (TSP). The first facility was built in Oromia in 2014, but as of early 2016, custom blended fertilizers were unknown by farmers around Jimma, whom had only ever encountered DAP and urea.

4.2.1 A "DAP equivalent" and "TSP equivalent" from bone char fertilizer

Direct comparison of DAP, whose chemical analysis is 18-46-0 (NPK) and bone char, whose chemical analysis is 0-32-0, is not possible due to the fact that DAP contains both nitrogen (N) and phosphorus, whereas bone char contains only P. If we wish to compare the value of DAP and bone char, the presence of nitrogen and the difference in concentrations of P must be taken into account.

DAP is 20.5% elemental P and 18% elemental N. Bone char is 14% elemental phosphorus and contains no nitrogen. Urea, a sole-nutrient nitrogen fertilizer widely available in Ethiopia, contains 46% elemental nitrogen. In order to create a valid comparison, it is possible to make a mixed fertilizer containing both bone char and urea such that it has the same amount and ratio of N and P as DAP. Such a fertilizer mix would contain of 1.46 kg of bone char and .39 kg of urea. A 1.85 kg bag of this new mixed fertilizer contains the exact same amount of primary plant nutrients (NPK) as 1 kg of DAP. We can therefore call a 1.85 kg unit of this new mixed fertilizer, one "DAP equivalent". TSP, which only has P, also contains 20.5% elemental P, and therefore, one "TSP equivalent" is equal to 1.46 kg of bone char.

4.2.2 Estimating the farm-gate price for TSP and urea

Before we can compare the farm-gate price of TSP and DAP to that of bone char and the mixed "DAP equivalent" fertilizer we must determine the farm-gate price for TSP and urea, which is an ingredient for the mixed fertilizer. There is no readily available record for farm-gate prices in Ethiopia, so we must create a novel method for farm-gate price using historical data.

Rashid, Minot & Ayele (2013) meticulously documented the cost buildups of fertilizers for each region of Ethiopia for the year 2012. In order to start calculating our farm-gate price estimates, we generate a ratio of the World Bank's 2012 world price[40] for DAP and urea for 2012 and the farm-gate prices for DAP and urea in Oromia from Rashid, Minot & Ayele (2013). This yields an Oromia farm-gate price to world price ratio of 1.65:1 and 1.70:1 for each DAP and urea. The average of the two ratios is 1.67:1. If we assume that all imported fertilizers have more-or-less the same cost accumulations then it should hold that we can accurately calculate the 2015 farm-

[40] Source: http://pubdocs.worldbank.org/en/469361480717943868/CMO-Historical-Data-Annual.xlsx, accessed December 16 2016.

gate prices of TSP and urea by multiplying the average ratio of the world price and the farm-gate price from 2012 (above) to the current world price of each fertilizer.

In order to test the accuracy of this method, we can compare the calculated 2015 farm-gate price of DAP in Oromia to the known farm-gate price of DAP. The farm-gate price for DAP near Jimma, Oromia during the research activities in 2015 was exactly 15.00 ETB per kilogram. The world price of DAP for 2015 was 434.33 USD. Applying the 1.67:1 ratio and converting the value to Ethiopian Birr[41] yields a price of 15.08 ETB per kilogram. We confirm that the above method for estimating Oromia farm-gate is accurate for the year 2015. Using the method described above, the estimated 2015 farm-gate price for urea in the Oromia region was 8.97 ETB per kg, while the farm-gate price for TSP (if it were commercially available) would be 12.65 ETB per kg.

4.2.3 Comparing the farm-gate price of bone char to TSP and DAP

Now that we have a value for the farm-gate price for urea, we can calculate the cost of the mixed "DAP equivalent" fertilizer, which is 8.96 ETB and 12.13 ETB per kilogram for each the low-cost and the high-cost scenarios. It is clear from table 4.2 that bone char is considerably less expensive than its imported competitors, even in the high cost scenario. The bone char and urea based "DAP equivalent", which contains 1.46 kg of bone char and .39 kg of urea is 20%-41% cheaper than it's substitute, DAP. This is a very encouraging finding. The "Dap equivalent" fertilizer mixture has the same fertilizer value as DAP, but costs significantly less.

[41] Exchange rate based on December 2015 ETB to USD from US treasury department: https://www.fiscal.treasury.gov/fsreports/rpt/treasRptRateExch/itin-12-31-2015.pdf

Table 4.2 Per kg cost comparison of bone char (BC) fertilizers to DAP and TSP

Cost scenario	Bone char fertilizer cost	Cost imported equivalent	BC % diff. to imported equivalent
TSP Equivalent			
low-cost	ETB 5.33	ETB 12.65	-57.89%
high-cost	ETB 8.42	ETB 12.65	-33.48%
intermediate	ETB 6.87	ETB 12.65	-45.69%
DAP Equivalent			
low-cost	ETB 8.96	ETB 15.08	-40.56%
high-cost	ETB 12.13	ETB 15.08	-19.59%
intermediate	ETB 10.54	ETB 15.08	-30.08%

This finding suggests that a producer will be able to charge prices that are well above the costs of producing the “DAP equivalent” and thus, generate a profit. The exact amount of profit a bone char fertilizer producer could expect is in following section, 4.3.

The difference in farm-gate price between bone char fertilizer and its imported substitute is even more pronounced for the “TSP equivalent”. The cost of the “DAP equivalent” is greatly increased by the addition of urea, which like the other imports, has accumulated many costs during importation and distribution. In our low-cost scenario, the “TSP equivalent” is less than half the price of TSP. This result signifies that bone char fertilizer may be a cheaper, local and equally effective substitute for TSP in the government’s fertilizer mixing facilities. Ethiopia is “importing new fertilizer ingredients for the first time in more than four decades” (ATA, 2014), which affords an opportunity for emerging bone char fertilizer producers to integrate their product into a fertilizer mixing program progam. With each facility capable of producing over 250,000 MT of fertilizer every year (ATA, 2013), the integration of bone char fertilizer as a component of the country-wide fertilizer mixing program may be the simplest and most far reaching method for getting bone char in the hands of Ethiopian farmers.

4.3 Profitability of bone char fertilizer production in Jimma, Oromia

The profitability of a bone char fertilizer producer depends upon the formulation (mixture) and market to which it is selling its product. For example, there may be a very large market for a sole-nutrient P fertilizer if the government is willing to integrate locally produced products into its national fertilizer mixing program. If this were the case, a fertilizer producer would be able to take advantage of the large profit margins associated with producing the “TSP equivalent”. It is unclear, however, that there would be a market pure bone char, a sole-nutrient P fertilizer, if it were marketed directly to farmers[42]. There is no other sole-nutrient P fertilizer in Ethiopia, causing risk averse farmers to potentially apply a discount to unfamiliar products (Heffernan & Ariga, 2012). If the central government is uninterested in integrating bone char into its mixing program, it may be necessary to produce the mixed “DAP equivalent” which is more expensive to produce and, therefore, cuts into profit margins. In the following section, we will present and maximize a production function for a firm producing both “TSP equivalent” and “DAP equivalent” bone fertilizer in Ethiopia. In the last part of this section, we will generate some estimates for the expected monthly profit of a bone char fertilizer producer in Jimma using the data from the collection experiment in chapter 2.

[42] This question is addressed in Chapter 6: Estimating farmer willingness to pay for bone char fertilizers with experimental auctions in Southwest Ethiopia.

4.3.1 Profit function for bone char fertilizer production

The first assumption in generating the model is that a fertilizer producer is responsible for acquiring bone residues (the principal factor of production) from collectors and that once residues are collected in large quantities, there is no other industry competing for use of the bones (i.e. chicken feed). The producer can control the quantity of bone residues available for production by adjusting the per kg price of bone residues. This relationship would be expressed by a supply function, such that increasing the purchasing price for bones would increase the quantity of bones collected. If the producer decides to increase the payout price to collectors and more bones are collected, the producer's revenue increases and per unit fixed costs decrease from economies of scale, but the marginal variable costs would increases because the unit cost of the primary factor of production (bone residues) increases. The research question we will answer below is what is the price a fertilizer producer must offer to bone collectors that will maximize profit of producing "TSP equivalent" and "DAP equivalent".

A simple production function for profit of producing a "DAP equivalent" or "TSP equivalent" from bone char fertilizer would be:

$$\pi = \left(\frac{Y_{pz}}{Z_{ratio}}\right)(R - C_{\mathrm{var}}) * X_s - C_{fix} \qquad \textbf{Eq. 4.1}$$

In equation 4.1 above, π is equal to profit, Y_{pz} is the yield of pyrolysis, Z_{ratio} represents the ratio of phosphorus in the imported substitute to that of bone char (import:bonechar), R is revenue,

C_{var} are the variable costs of production, C_{fix} are the fixed costs of production and X_s is the supply of bone residues available for production.

It is necessary to include Y_{pz} because bone residues lose mass during pyrolysis. The result is that if Y_{pz} is equal to 72%, such that 1.39 kg of raw bone residues are required to produce 1 kg of bone char. If we are producing a bone char based "DAP equivalent" or "TSP equivalent" fertilizer, the Z_{ratio} is equal to 1.46, which is the quotient of the percent elemental P in DAP/TSP (20.5%) and the percent elemental P in bone char (14%). The implication of Z_{ratio} is that 1.46 kg of bone char would be required to generate the equivalent amount of P in 1 kg of DAP/TSP. The combined impact of Y_{pz} and Z_{ratio} means that a total of 2.03 kg of bone residues are required to produce one "DAP equivalent" or one "TSP equivalent" of bone char fertilizer.

We can further breakdown variable costs into processing costs**,** C_{proc}, and the cost of 1 kg of bone residue, P_b. If the fertilizer being produced is the "DAP equivalent" then C_{proc} would include the cost of the added urea (~3.51 ETB per "DAP equivalent"). We also multiply P_b by $\left(\frac{Z_{ratio}}{Y_{pz}}\right)$. This slightly change the interpretation of P_b, which in the form $\left(\frac{Z_{ratio}}{Y_{pz}}\right) * P_b$,, becomes the price of the total quantity of bone residues required to produce one "DAP equivalent" or "TSP equivalent". With these new components, the function becomes:

$$\pi = (R - (C_{proc} + \left(\frac{Z_{ratio}}{Y_{pz}}\right) P_b)) * \left(\frac{Y_{pz}}{Z_{ratio}}\right) * X_s - C_{fix} \qquad \textbf{Eq. 4.2}$$

As mentioned above, we hold the assumption that a fertilizer producer will be able to control the supply of bone residues, X_s, by changing the per kilogram payout price for bone residues, P_b. The supply of bones, therefore, can be represented by a supply function, $X_s(P_b)$. For the sake of simplicity, we represent bone supply as a linear function.

$$X_s = A + BP_b \qquad \textbf{Eq. 4.3}$$

In equation 4.3, the supply of bones, X_s, increases with an increase in price, P_b. The values for A and B, which are constants, can be derived from experimental data. Later in this section, we will use data from the collection experiment to calculate X_s. Replacing X_s in equation 4.2 with the supply function from equation 4.3 yields the following:

$$\pi = ((R - (C_{proc} + \left(\frac{Z_{ratio}}{Y_{pz}}\right)P_b)) * \left(\frac{Y_{pz}}{Z_{ratio}}\right)(A + BP_b)) - C_{fix} \qquad \textbf{Eq. 4.4}$$

It is now possible to maximize profit by taking the derivative of the profit function, $\pi(P_b)$ with respect to P_b and identifying P_b^*, the profit maximizing price at which to purchase bone residues for producing one "DAP equivalent" or "TSP equivalent" from collectors. Taking the derivative of profit with respect to price for bone residues gives the equation:

$$\left(\frac{\partial \pi}{\partial P_b}\right) = 0 = \left(\frac{Y_{pz}}{Z_{ratio}}\right)(BR - BC_{proc} - \left(\frac{Z_{ratio}}{Y_{pz}}\right)A - \left(\frac{Z_{ratio}}{Y_{pz}}\right)2BP_b) \qquad \textbf{Eq. 4.5}$$

Solving equation 4.5 for P_b yields:

$$P_b^* = \left(\frac{Y_{pz}}{Z_{ratio}}\right)\frac{(BR - BC_{proc} - \left(\frac{Z_{ratio}}{Y_{pz}}\right)A)}{2B} \qquad \textbf{Eq. 4.6}$$

4.3.2 Profit and output for a fertilizer producer in Jimma

We will be maximizing profit for a firm operating under the low-cost and the high-cost scenario for both the DAP and TSP equivalent fertilizers. The first step in maximizing the expected profit for a fertilizer producer is determining the values of the constants for the supply function depicted in equation 4.3, above. We can identify the values of the supply function from the data of the collection experiment described in chapter 3. It should be stated, however, that the profit estimates generated from the collection data are almost certainly incorrect and represent a fairly pessimistic outlook for the profitability of a bone char fertilizer producer in Jimma. The collection experiment had numerous problems, which we have already described, and which undoubtedly pushed down the quantities of bones that were collected during the trail.

The average quantity of bone residues collected was 2687 kg per day when the per kg payout price was 2.00 ETB per kilogram. The intake fell to an average of 2095 kg per day when the payout price was lowered to 1.25 ETB. These two points can be used to generate the linear supply function, X_s=1108.34 + 789.33P_b

Using the formula presented in equation 4.6 we are able to find P_b^*, the profit maximizing price at which to purchase bone residues. The values for B and A are in the supply function specified in the above paragraph. The values for C_{proc} of the low-cost and high-cost scenarios for the "TSP equivalent" and "DAP equivalent" fertilizers are specified in table 4.1. The value for Y_{pz} is 1.46, the ratio of the percentage of elemental P in DAP/TSP to the elemental P bone char. Lastly, the marginal revenue of "DAP equivalent" and "TSP equivalent" will be equal to the farm-gate price of the imported equivalent: 12.65 ETB for one unit "TSP equivalent" and 15.08 ETB for one unit "DAP equivalent". We will also calculate profits if marginal revenues of "DAP equivalent" and "TSP equivalent" were equal to 90% of their imported equivalents: 11.39 ETB for one unit "TSP equivalent" and 13.57 ETB for one unit "DAP equivalent". The results of this exercise are presented in table 4.3.

Table 4.3 Maximized profit for firms producing bone char fertilizers using data from collection experiment.

Fertilizer *Scenario*	**Marginal Revenue**	P_b^*	**MT imported equivalent**	**Total monthly profits ETB**	**Total monthly profits USD**
DAP Equivalent					
low-cost	ETB 15.08	ETB 1.44	33.19	ETB 156,753	USD 7,572.59
high-cost	ETB 15.08	ETB 1.11	29.26	ETB 113,870	USD 5,500.96
low-cost	ETB 13.57	ETB 1.07	28.88	ETB 109,951	USD 5,311.64
high-cost	ETB 13.57	ETB 0.74	24.95	ETB 72,996	USD 3,526.39
TSP Equivalent					
low-cost	ETB 12.65	ETB 1.74	33.19	ETB 199,054	USD 9,616.14
high-cost	ETB 12.65	ETB 1.44	29.26	ETB 156,154	USD 7,543.67
low-cost	ETB 11.39	ETB 1.43	28.88	ETB 154,968	USD 7,486.40
high-cost	ETB 11.39	ETB 1.13	24.95	ETB 116,519	USD 5,628.96

It is immediately clear from table 4.3 that the profits of producing the "TSP equivalent" are much higher than those of producing a "DAP equivalent". This result suggests that fertilizer producers have significant incentives to find a market for pure bone char fertilizer in Ethiopia, whether it is through government mixing facilities or marketing directly to farmers.

Lastly, even with the relatively small amount of fertilizer that would be produced every day (.83-1.3 MT) for the scenarios in table 4.3, the act of producing bone char would have a significant impact on fertilizer availability and costs in the area immediately surrounding Jimma. The average farm size in Oromia is 1.32 ha (CSA & World Bank, 2013). The average hectare of cultivated farmland in Ethiopia receives ~40 kg/ha of fertilizer per year (Spielman, Byerlee, Alemu, & Kelemework, 2010). The quantities of bone char fertilizers produced in table 4.3 are sufficient to satisfy fertilizer demand for ~5750 - 9000 farmers annually.

4.3.3 Profits and outputs for scaled operations

It is worth reiterating that the values in table 4.3 represent a very pessimistic outlook for the profit of a bone collection facility. Figure 4.1 shows how profits change with increases in the quantity of bones collected per day. In Jimma, for example, there are at least 4136 kg of bone residues entering the waste stream on a daily basis (Getahun et al., 2012), and that is negating the existence of a years-long store of years-old bone residues. If all or nearly all of these bone could be collected at 1.67 ETB, which is the average payout price from the collection experiment, the monthly profits for a producer in Jimma would be between 6,000 USD and 18,000 USD, and provide fertilizer to 14,000 farmers annually.

If Addis Ababa generated the same quantities of bone waste per capita as the people Jimma, which is almost certain given that Addis Ababa is the richest city in Ethiopia, the total quantity

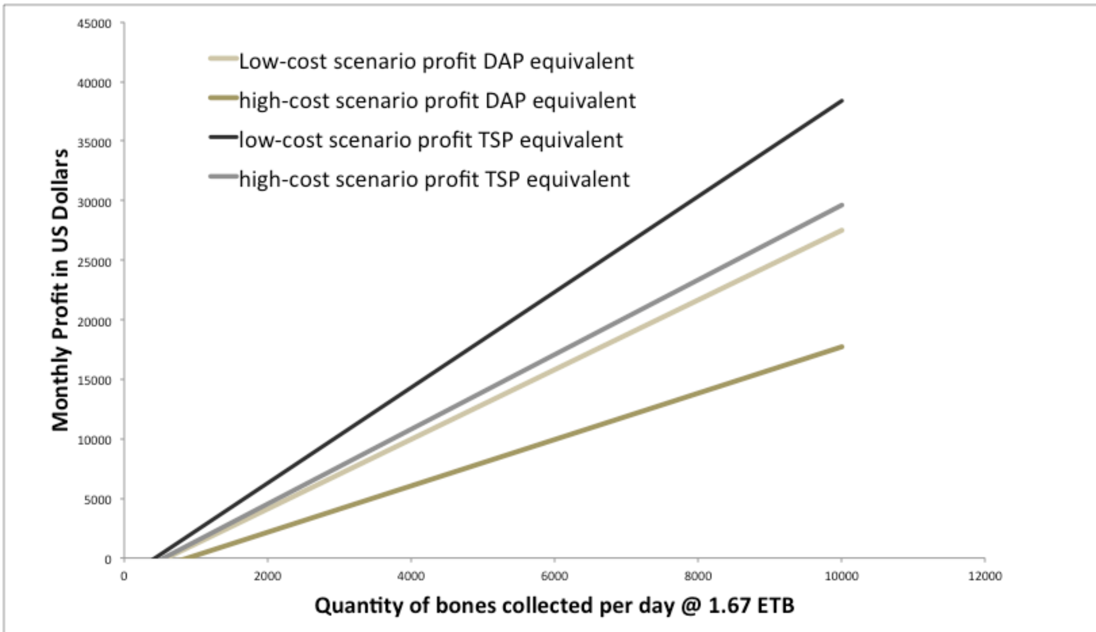

Figure 4.1 Profits for fertilizer producers with rising daily output and *Pb* fixed at 1.67 ETB per kilogram

of bone residues generated every day would equal 91,000 kg per day[43]. With these quantities, a fertilizer producer could generate 10 million USD worth of fertilizer annually, capable of satisfying the fertilizer demand of over 310,000 farmers.

For each of the scenarios graphed in figure 4.1, if more than 1000kg of bone residues are collected daily, marginal revenues exceed marginal costs of production. In our collection trial, the lowest quantity collected in a single day was 1753 kg and we had to close the collection site in the morning because it had run out of money. This tells us that even small towns may be able to support a small-scale bone char fertilizer production facility. In the end, whether large-scale or small-scale, there are clear, profit-based incentives for private firms to produce bone char fertilizer in Ethiopia with no need for government subsidies.

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[43] Jimma, a city of 207,00 people, produces ~4136 kg of bone wastes everyday (Getahun et al., 2012). Addis Ababa has a ~4,570,000 inhabitants. The assumption is that Addis Ababa would produce the same per capita bone wastes.

Chapter 5. Estimating Farmer Willingness to Pay for Bone Char Fertilizers

We have been able to demonstrate that enough bone residues can be collected to support a profitable bone char producer in Jimma, Ethiopia. We have been able to show that the farm-gate price of bone char fertilizers, both as a substitute for TSP and DAP, are significantly lower than their imported equivalents. One research question remains: are farmers are willing to pay for bone char fertilizers at prices that are commensurate with the costs of production? In order to answer this question, we performed a series of experimental auctions in two rural *kebeles* of Mana *woreda*, near Jimma, Ethiopia in which a bag of DAP fertilizer, a bag bone char based “DAP equivalent” fertilizer and a bone char only fertilizer (“TSP equivalent”) were all offered for sale. The goals of conducting these experimental auctions were to estimate the market price (demand) of bone char fertilizer (both as a substitute for DAP and as a sole nutrient P-fertilizer), determine the discrete characteristics of bone char fertilizer that are driving farmer willingness to pay, and lastly, to determine both the socio-economic and agronomic characteristics of farmers that impact the willingness to pay for bone char fertilizers. In the following chapter we will describe and summarize the results of these experimental auctions as well as discuss the implications of our findings for the demand of bone char fertilizer in Ethiopia.

5.1 Isolating the discrete characteristics of bone char fertilizer

Determining the WTP for bone char fertilizer is complicated by the fact that it does not physically resemble the commercial fertilizers that are currently available on the Ethiopian market[44] (DAP and urea). It is not clear whether farmers prefer domestic fertilizer products as compared to imports or if there is an acceptability constraint resulting from discomfort associated with the fact that bone char is derived from animal bones. In this context, we define an acceptability constraint as a zero or negative WTP such that an individual would require compensation in order to use the product. Such a constraint would likely arise from fear of negative health affects or cultural taboo associated with recycled waste products (Danso, Drechsel, Fialor, & Giordano, 2006).

Figure 5.1 From left to right: DAP, bone char only (BC), and "DAP equivalent" (MIX)

Adding to the difficulty of predicting the WTP and acceptability of bone char fertilizer in Ethiopia is the lack of commercially available sole-nutrient phosphorus fertilizers in Ethiopia. As we had mentioned previously, DAP is the only commercially available phosphorus fertilizer in

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[44]The bone char granules used in this study were black with a size guide number of 800. DAP is white in color with a SGN no greater than 350.

Ethiopia. To address the problem of a valid comparison, we used the mixed fertilizer described in section 4.2 in order to create a "DAP equivalent" fertilizer from bone char and urea. By creating a "DAP equivalent", we have effectively controlled for nutrient values. Any relative consumer valuation of the DAP and the mixed fertilizer will, therefore, be based solely on the combination of the physical characteristic of bone char, the primary materials from which it is derived and its domestic origin. We will call these characteristics non-nutrient characteristics. Subsequently, by comparing the valuation of the mixed bone char fertilizer with unadulterated bone char (described as "TSP equivalent in section 4.2) we are able to determine the relative value of bone char as a sole-nutrient P fertilizer independent of non-nutrient characteristics.

5.2 Experimental Design

The experiment was conducted in adjacent *kebeles* of the Mana *woreda*, located in the Eastern section of the Jimma Special Zone, Oromia, Ethiopia. The *woreda* is less than an hour's drive from the city of Jimma, though many of the sites visited were only accessible by foot. Mana *woreda* has a population of ~150,00 inhabitants, of which 97% are rural (CSA, 2007). The principle cash crops of the are *khat* and coffee (Abbajobir, 2011; Muche, Endalew, & Koricho, 2014).

In partnership with our local partner institution, Jimma University and extension agents[45], we identified a community leader in each *kebele* to act as a liaison with the farmer community. The development agent (DA) and community leader worked to together to notify farmers about upcoming auction events, identify a suitable meeting location and to gather 30 individuals to

[45] In Ethiopia, they are officially called development agents (DAs).

attend each auction on a prearranged date and time. The community leader was paid a small fee for helping to organize each successful auction.

Once all the participants arrived, the head enumerator offered a synopsis of the day's activities from a prepared text in the two local languages (Amharic and Oromifa). All subsequent group communications were conducted in both Amharic and Oromifa, while individual conversations were realized in the language preferred by the participant. All enumerators were fluent in the two principal local languages. Following the introduction, each participant was interviewed by one of five enumerators. The interview detailed each participant's socio-economic information, farming practices and fertilizer preferences. Upon the completion of the survey, participants were given four bidding slips (with a number corresponding to their survey) and 75 ETB (~3.50 USD). The participants were told that the money was a fee meant to compensate for the time they had taken from their work to participate in the auction, and that they were "not obligated to use the money during the auction". This pretext is meant to ensure that the fee only serves the purpose of relieving the liquidity constraint often associated with poor farmers, which can lead to lower-bound truncation ("zero" bids) (Beltramo, Blalock, Levine, & Simons, 2015; Morawetz, De Groote, & Kimenju, 2011). By referring to the payment as a "fee" we are able to avoid the payment being seen as a quid pro quo for which participants should reciprocate by spending more during the auctions, which would bias the bidding (Loureiro, Umberger, & Hine, 2003).

At the conclusion of participant interviews, the head enumerator read a prepared explanation to the group of how the Vickrey second-price auction format works. In a Vickrey second-price auction, all participants bid for a product simultaneously, and the individual with the highest bid wins the item and pays (out of pocket) the price of the second highest bid (Lusk, 2003; Vickrey, 1961). This method is theoretically incentive compatible, with participants offering their true or maximum WTP. We say that the Vickrey second-price auction is incentive compatible because the optimal strategy is to bid one's maximum WTP independent of risk aversion (Cox, Roberson, & Smith, 1982; Morawetz et al., 2011; Vickrey, 1961). Alternatively, in a first-price auction, gains can be made if the participants bid for less than the maximum WTP (Morawetz et al., 2011).

The head enumerator followed the description of the bidding protocol by explaining that in a second-price auction, the optimal strategy for a participant is to bid their max WTP. This explanation was included because there is evidence that explaining the nature of the incentives built into an auction's format will motivate true demand-revealing behavior and minimize misconceptions of the auction rules (Corrigan & Rousu, 2008; Plott & Zeiler, 2005). Time was allowed for questions and clarifications on auction protocols.

The auction began with a practice or test round in which a bottle of cooking oil was offered. This test round is meant to improve the participants' understanding of the auction and to demonstrate that actual money would be exchanged during the experiment. In testing improved cornmeal in Kenya, De Groote *et al.* 2011 included a test round using cupcakes to help participants understand the procedure. This was largely necessary because farmers are likely to be more familiar with first price auctions (Cox et al., 1982) and there is considerable evidence that second-price auctions require practice in order for participants to learn the dominant strategy (Drichoutis, Nayga, & Lazaridis, 2011; Harrison, 2006).

Following the test round, participants were invited to take part in auctions for three different bags of fertilizer containing the following: (1) 5 kg diammonium phosphate (DAP), (2) 7.32 kg bone char mixed with 1.96 kg urea (5kg "DAP equivalent" or MIX), and (3) 7.32 kg bone char (5kg "TSP equivalent" or BC). We formulated the MIX fertilizer so that it would have the exact same amounts of elemental phosphorus and nitrogen as DAP. The bag of BC fertilizer had the same amount of elemental phosphorus as DAP and MIX, but contained no nitrogen. Each bag was labeled with the name of the fertilizer and the number of kilograms of elemental nitrogen, phosphorus and potassium (K).

As previously mentioned, a direct comparison of WTP for the bone char only fertilizer to DAP is complicated and of limited usefulness. It is impossible to decouple the impact of the lack of nitrogen to the non-nutrient characteristics of the fertilizer. By comparing the MIX fertilizer to DAP, however, we are able to control for nutrient values and measure the impact of the combination of the non-nutrient characteristics on consumer WTP. By introducing the MIX fertilizer, it becomes possible to measure whether farmers discount the lack of nitrogen in BC, since the only difference between the two products is whether or not nitrogen has been added.

The order of bidding was randomized prior to each auction. There is evidence that the order in which the items are offered in an auction can affect WTP, called order effects (Morawetz et al., 2011). Order effects are largely a consequence of learning more about the process during bidding and by participant fatigue (List & Shogren, 1999). By performing a practice round prior to bidding and randomizing order of items in the auction, we hope to effectively control for order effects.

Before each item was bid upon, the head enumerator gave a short description of each fertilizer, detailing where the fertilizer was manufactured and its nutrient contents as well as allowing ample time for participants to inspect and handle the products. Providing sufficient non-price information will act to minimize bidder affiliation (*i.e.*, the tendency for bidders that lack information to adjust their bid to some exogenous value such as the winning bid of a previous auction) (Lusk, Feldkamp, & Schroeder, 2004; Milgrom & Weber, 1982). Therefore we devoted significant amounts of time writing the descriptions of each of the fertilizers[46] and testing them in pilot auction to ensure that participants would understand the descriptions and that no descriptions generated a bias in the bidding. No price information for any fertilizer was presented to participants.

After the description of each fertilizer, the head enumerator asked participants to restrain from discussing bidding strategies and bidding amounts until the conclusion of the day's auction activities. Bidding was performed in silence, and the winner was required execute the payment prior to the start of the next round of bidding. There were no instances in which the winner refused to pay for fertilizer, which indicates a near universal understanding of the auction format and procedure.

At the conclusion of the auction activities, a subset of participants were randomly selected for a follow-up interview, in which we asked whether the individual believed that the selling price was accurate, the characteristics of each fertilizer that they considered most desirable, and how the bone char fertilizer could be improved to increase its value.

[46] The descriptions of the fertilizers in both English and Amharic are available in appendices C and D.

5.3 Theoretical model for relative WTP

In the following section, we will describe a theoretical model showing how a rational farmer's willingness to pay for fertilizers in our auction is based on profit maximization. In order to do this, we utilize the production function described in section 2.4. Once we construct the model, we will describe how the outcomes from the experimental auctions can be described in the context of our model.

From section 2.4, we know that farm profit with respect to fertilizer as the sole factor of production has the production function:

$$\pi = PY(x_f) - rx_f \qquad \text{Eq. 5.1}$$

In order to create the model of relative WTP, we need to be able to calculate profit of using bone char with respect to the quantity of fertilizer applied, x_{bc}, and profit of using DAP with respect to the quantity of fertilizer applied, x_{dap}.

$$\pi_{dap} = PZ(x_{dap}) - r_{dap}x_{dap} \qquad \text{Eq. 5.2}$$

$$\pi_{bc} = PY(x_{bc}) - r_{bc}x_{bc} \qquad \text{Eq. 5.3}$$

Equations 5.2 and 5.3, represent the profits from applying DAP fertilizer and bone char fertilizer, respectively. In the above equations, the terms $Z(x_{dap})$ and $Y(x_{bc})$ are the yield response function for DAP and bone char fertilizer. By introducing the auction format, farmers are no longer able to influence the quantity of fertilizer purchased. To represent this in our model, this we impose the restriction $x_{dap}=x_{bc}=x_q$. Participants can no longer maximize profit by changing the quantity of fertilizer they apply to their crops. Participants are, however, able to change their bid price for x_q kilograms of bone char or DAP. If our experiment is incentive compatible then as participants compete for the last unit of profit, the maximum willingness to pay for x_q kilograms of fertilizer will asymptotically approach the total expected revenue generated by that quantity of fertilizer. As a consequence of this competitive behavior, expected profit will be driven to zero. In the context of experimental auctions, therefore, the value of profit (π) in Equation 5.2 and 5.3 can be set to zero. Solving equations 5.2 and 5.3 for fertilizer price (r_{dap} and r_{bc}) gives the equations,

$$r_{dap} = \frac{PZ(x_q)}{x_q} \qquad \text{Eq. 5.4}$$

$$r_{bc} = \frac{PY(x_q)}{x_q} \qquad \text{Eq. 5.5}$$

The equation above tells us that the maximum WTP for fertilizer in our experimental auction (demand) is equal to the expected average per kilogram revenue generated by an application of x_q kilograms of fertilizer. In other words, the max WTP for fertilizer in our experiment is equal to the value of the average physical product.

The expected revenue is equal to the product of crop price and the output of the yield response function. The difference in price, therefore, is equal to the difference in expected revenues generated by applying x_q kilograms of DAP fertilizer applying x_q kilograms of bone char fertilizer.

$$\triangle r = r_{dap} - r_{bc} = \left(P\frac{Z(x_q)}{x_q} \right) - \left(P\frac{Y(x_q)}{x_q} \right) \qquad \text{Eq. 5.6}$$

The meaning of equation 5.6 is such that if Δr is positive, then a rational farmer's bidding behavior expresses the belief that DAP fertilizer will generate higher yields and revenues than the bone char fertilizer. If Δr is equal to zero, then the farmer believes that revenues from applying x_q kilograms of DAP and the bone char fertilizer will generate identical yields and identical revenues. If Δr is negative, the farmer must believe that bone char will improve yields and revenues over the DAP fertilizer.

5.4 Empirical Model

In theory, farmer WTP is driven by their valuation of discrete characteristics of a given product (De Groote, Kimenju, & Morawetz, 2011). In our experiment, where BC and MIX fertilizers are distinct in many ways from DAP, our ability to infer about discrete characteristics and marketing messages (i.e. whether the product is domestically produced, whether it is a biofertilizer, product color, product bag size, *etc.*) is limited. Each product is composed of many characteristics that cannot be disentangled, so comparative WTP for consumer *i* can be regressed on the product without specifying discrete characteristics.

$$bid\_price_i = \alpha + F'_i\beta + e_i \qquad \text{Eq. 5.7}$$

where bid_price_i is the amount bid by individual *i*, F_i is a categorical variable for the fertilizer *(f)* being bid upon with DAP as the omitted category, and e_i as an error term.

The data comes from an experiment in which each participant was able to submit a bid for all three fertilizers, which introduces correlation in the error terms, so we must include a unique error term u_i for each the consumer in our model.

$$bid\_price_i = \alpha + F'_i\beta + u_i + e_i \qquad \text{Eq. 5.8}$$

In dealing with these error terms, fixed effects (Beltramo et al., 2015) and random effects (De Groote et al., 2011) estimators are commonly employed. Our experiment has an orthogonal design, where every cross-sectional unit faces each treatment an equal number of times. In the case of a panel set comprised of orthogonal treatment indicator variables, the standard errors are identical for FE and RE, such that the "choice between a fixed and random effects estimator is moot… because they are the same estimator." (Oaxaca & Dickinson, 2005). Given this freedom, we prefer the random effects model, which unlike the fixed effects model, allows for the estimation of time invariant characteristics (Hill, Griffiths, & Lim, 2011). The choice must still be made between pooled ordinary least squared regression and random effects (Oaxaca &

Dickinson, 2005). This can be tested with a standard F-test (Hill et al., 2011), and we were able to confirm that error term u_i is not equal to zero.

It may be the case that WTP varies among consumers in systematic ways. This can be analyzed by including variables for consumer characteristics. Instead of creating a variable for each of the demographic variables, it is convenient to present consumer characteristics as a vector C_i containing Z characteristics.

$$bid\_price_i = \alpha + F'_i\beta + C'_i\chi + u_i + e_i \qquad \text{Eq. 5.9}$$

The consumer characteristics in vector C_i can be broken down into two categories, socio-economic variables and farming practices and fertilizer preferences. The socio-economic characteristics that were measured and may influence WTP were age and formal education, the latter of which has been shown to increase fertilizer adoption (Zerfu & Larson, 2010). We have decided to include tropical livestock units (TLU) adjusted for sub-saharan Africa region (Njuki et al., 2011) and farm size as economic measures. In the set of variables for farming practices and fertilizer preference, we will explore five regressors: a variable for the proportion of years that a participant purchases fertilizer; a binary variable for whether or not the participant uses non-commercial fertilizers such as manure or compost; a binary variable for whether or not a participant has regular contact with a development agent (DA) (at least once per month), whether they preferred imported fertilizer over domestically produced products and whether the participant responded positively to the statement, "I would pay extra money for a fertilizer if I knew it would be available on the market when I needed it most." For future reference, we will call these variables frequency of fertilizer use, alternative fertilizer use, regular contact with DA, import preference and availability premium, respectively.

The specification from Eq. (3) will give us the direct effects of consumer characteristics on WTP (Lusk et al., 2004). While the direct effect of consumer characteristics on bid price provides useful information, we are more interested in the effect of consumer characteristics on their preference for a particular product. We can include this in the model as a Matrix *M* (*Z×F)*, where each cell m_{zf} of the matrix is the coefficient of the effect of consumer characteristic *z* on WTP for a fertilizer *f*. With the interactions, the general model becomes

$$bid\_price_i = \alpha + F'_i\beta + C'_i\chi + F'_i\beta * C'_i\chi + u_i + e_i \qquad \text{Eq. 5.10}$$

5.5 Methodology for data analysis

The data was analyzed by comparing average prices for each of the three fertilizers included in the auction and through regression of various specifications of the random effects general least squares (GLS) model described above.

In experimental auctions, the WTP can differ greatly from the market-clearing price (Morawetz et al., 2011). This is not of particular concern because the goal in our experiment is to analyze the demand of a novel good relative to preexisting substitute, which we will call a reference product. The difference in WTP between goods is often the most useful and reliable estimates coming out of experimental auctions (Hoffman, Menkhaus, Chakravarti, Field, & Whipple, 1993; Lusk et al., 2004). Since the Vickrey second-price auction is an incentive compatible, revealed preference format, the average bid amount of each fertilizer represents, in theory, an unbiased estimator of WTP. This does not, however, preclude the possibility of underbidding due to strategic behavior (Lusk et al., 2004) or other unusual bidding that is not congruent with what we believe to be incentive-based behavior.

Similar to De Groote *et al*. 2011 and Beltramo *et al.* 2015 we used a shortened model, the GLS random effects specified in Eq. (2), to compare WTP of the three fertilizers. Using the specification from Eq. (4), two mid-sized models were regressed, one with cross-effects of only socio-economic variables, the other only with farming and fertilizer variables. We also tested a longer specification with cross-effects for both farming and fertilizer variables as well as socio-economic variables.

5.6 Descriptive Statistics and auction results

A total of 119 individuals came to the auctions, all of whom consented to be interviewed for the initial survey. Only 4 of the 119 participants were female. Because so few participants were female we do not include a gender variable for the regressions in section 5.7.

Nearly all farmers grow maize as their main crop (96%). The average farm size for individuals participating in our experiment is 1.10 ha. This is slightly below the average farm size of 1.32 ha reported by government data for the Oromia region (CSA & World Bank, 2013). Average annual household income reported by participants was 7081 ETB or ~$345 USD, which is far from the national average income of 11,101 ETB or $542 USD for farms of similar size reported by (Headey et al., 2014). We asked participants to estimate their incomes for the past year, which is

Table 5.1 Consumer characteristics summary

Category	Variable	Mean	Std. dev.
Demographic	Female (share of total)	0.03	0.18
	Age	41.13	11.58
	Education	3.75	2.80
Economic	Annual household income (100's of ETB)	70.81	43.24
	Annual per capita income[1] (100's of ETB)	12.07	8.90
	Tropical livestock units[2]	2.34	1.62
	Farm size (ha)	1.10	0.80
Farming and Fertilizer	Main Crop (share of total)		
	corn	0.96	--
	coffee	0.02	--
	soybean	0.01	--
	teff	0.02	--
	Renting land	0.12	0.32
	Regular contact with DA	0.78	0.42
	Annual fertilizer consumption (kg)	68.81	31.98
	Frequency of fertilizer use[3]	1.44	0.55
	Alternative fertilizer use	0.44	0.50
	Fertilizer importance for profit	0.87	0.33
	Fertilizer access problem[4]	0.11	0.35
	Availability premium	0.31	0.46
	Import preference	0.23	0.42
	Fertilizer knowledge[5]	0.02	0.13
	Total participants (N)[6]	118	--

[1]The annual per capita income is the household income divided by the number of individuals within that household
[2]Cattle=1.0; sheep=0.2; goat=0.2 (Njuki *et al.* 2011); [3]The number of times in the previous three years that the individual purchased fertilizer, divided by three; [4]The proportion of farmers that could name one primary plant nutrient in either urea of DAP; [6]The observations for one individual were dropped from the sample due to their extreme bidding values

unlikely to yield accurate results. Tropical livestock units are a weighted census of the livestock holdings of a household. For Sub-Saharan Africa, cattle sheep and goats equal 1.0 , 0.2 and 0.2 , respectively. The average farmer in our trial has 2.13 cattle and 1.08 sheep and goats, for an average 2.34 TLUs. Assets, of which livestock and land is likely to be the most significant, are better measures of welfare than income since they reflect a "household's ability manage risk and meet consumption requirements" (Njuki et al., 2011). As a consequence, we will not use income in our model, but we will include farm size and TLUs. De Groote *et al.* 2011 used livestock as the sole economic regressor in a model for measuring WTP for various varieties of maize in Kenya.

A very high number of individuals (78%) had contact with development agents at least once per month during planting season, which is much higher than the average observed in previous studies at the regional and national levels (Gebru, Asayehegn, & Kaske, 2012; Gilligan, Hoddinott, & Taffesse, 2009). Previous work suggests that contact with development agents increases food security (Gilligan et al., 2009) and income (Dercon, Gilligan, Hoddinott, & Woldehanna, 2009). The method through which we identified participants for our experiment (leveraging DA and community leader contact) is likely the reason for this unusually high number. The DA was much more likely to involve individuals with whom he had previous contact.

All but one individual stated that their average annual fertilizer consumption was a non-zero number. This is a surprising figure considering the relatively low proportion of fertilized land in the country lies between 19-53% (Headey et al., 2014; Moller, 2015; Rashid et al., 2013) and the farmland planted to maize in Oromia could have fertilizer use rates as low as 15% (Rashid et al., 2013). It is possible that these high rates of fertilizer use are related to access to extension professionals within the sample. Additionally, if we divide each participants stated annual fertilizer consumption (kg) by the size of their farm (ha), we are able to calculate the average fertilizer application rate per hectare of farmland. The average fertilizer application rate per hectare of farmland for participants in our experiment is nearly 70 kg / ha, which is twice that of the national average[47] (Headey et al., 2014; Spielman et al., 2010). Lastly, we asked how many times participants had purchased fertilizer in the past three years: 55% of farmers had applied fertilizer one or zero times and only one individual purchased fertilizer each of the past three years. The average farmer in our study purchases fertilizer approximately once every two years, which is very close to the most recent reports of the national average of smallholders that use fertilizer, 50-53.1% (Headey et al., 2014; Moller, 2015). The frequency variable, while not as specific as say, the variable for annual fertilizer consumption, appears to be much more accurate, which is why we have chosen include fertilizer use frequency in our model, while excluding annual consumption.

Only 11% of farmers (n=13) stated having problems with access fertilizer on the market, however, 30% of participants said that they would be willing to pay a premium if they knew that fertilizers would be available on the market when they needed them most. The number of farmers willing to pay extra for a fertilizer if it were available when they needed it most closely resembles the national average (32%) of farmers that cite the lack of supply or late arrival of fertilizers as constraining usage (Moller, 2015). Farmers also seem to prefer locally produced fertilizers (77%) over products imported from China, the current source of virtually all Ethiopian

[47] While it is unlikely that farmers are accurately reporting the application rates of fertilizer, they seem to have a very clear understanding of the costs of fertilizer. By dividing the farmers stated average annual fertilizer spending by annual amount of fertilizer purchased (kg), the average outcome was 15.083 ETB per kg with a standard deviation of 1.18 ETB. The prevailing price for DAP at the time of the auction was 15 ETB per kg.

chemical fertilizers (Rashid et al., 2013). A slight minority (44%) of farmers stated they had used alternative soil amendments in the past.

Interestingly, only 3 of 119 individuals were able to name the primary plant nutrients in either urea or DAP. As mentioned earlier, this suggests that farmers lack the basic technical knowledge to discuss fertilizer attributes using even the most basic language. Interestingly, 87% said that fertilizer is important for improving incomes. It would appear that farmers understand the importance of fertilizers but are heavily reliant on others (extension workers, university researchers, NGOs) for information on fertilizer selection and application.

There were 357 observations (119 participants submitting a bid for each of the three fertilizers), and all bids were non-zero. The bids of one individual were dropped from the statistics reported in table 5.2 and subsequent analysis due to the fact that the individual's bid for DAP was more than 700% the market value (likely implying that he did not understand the auction set up).

Table 5.2 Willingness-to-pay results summary

Product	**Obs.**	**Mean Bid**	**Std. dev.**	**Median Bid**	**Mean Bid**	**Mean price paid**
DAP	118	53.04*	31.53	50.00	153.33ŧ	122.50
BC	118	52.02*	30.54	45.00	127.5	107.5
MIX	118	53.91*	25.44	50.00	111.25	100.00

*Average bid price is significantly greater than zero at $p < 0.01$ level ŧOne individual bid 550 ETB (more than 700% market value) for DAP. We will not include this bid in our reporting of average winning bid for DAP.

The results in table 5.2 show that the average bid amount for each of the three products is greater than zero. We performed a one-way t-test to determine if the average bid prices for each of the three products was significantly greater than zero, and the test reveals that every bid is significantly greater than zero at the $p < .01$ level of significance. This result allows us to address a question that until now had gone unanswered: are Ethiopian farmers willing to accept a fertilizer made from animal bones? With all participants submitting non-zero bids for both the MIX and BC fertilizers and the average bid significantly greater than zero, we can conclude that there is no acceptability constraint for domestically produced, bone-based P fertilizer among Ethiopian farmers in our sample.

Figure 5.2 Farmer executing transaction at experimental auction (photo: Yared Tadesse)

Additionally, if there are no acceptability constraints and farmers believe that the stated nutrient values of the fertilizers in the auction are correct then it would be reasonable to expect that MIX and DAP fertilizers, which have identical amounts of primary plant nutrients, would have very similar WTP values. The difference in WTP is less than 1 etb ($0.05 USD), with participants willing to pay a very small premium for the MIX fertilizer (though this difference is not statistically significant). Returning to our theoretical model from section 5.3, this finding suggests that participants felt that DAP and MIX fertilizers would generate equal yields.

There appears to be a slight discount for BC as compared to the other two fertilizers (but again, this difference is not statistically significant). This was to be expected, since the BC fertilizer contains no nitrogen and the bag weighed ~2kg less than the bag of MIX fertilizer. The discount, however, is very small (1.87 ETB and 1.02 ETB less than the MIX and DAP fertilizers, respectively). While value of the urea used to make MIX fertilizer is ~17.40 ETB greater than the BC product, farmers were only willing to pay an extra 1.87 ETB on average for the addition.

The information can be interpreted in two ways. The first interpretation is that farmers value phosphorus more highly than nitrogen and they willing to purchase a sole-nutrient phosphorus fertilizer at little to no discount from what they would pay for DAP (which contains nitrogen). If we were to take this view, it would imply that there is significant demand for sole-nutrient phosphorus fertilizers. If there his high demand for sole-nutrient P fertilizers in Ethiopia, it may be possible to market directly to farmers if the government allows bone char fertilizer to enter the conventional fertilizer value chain, and financing and distribution systems.

A likely alternative explanation, however, is that farmers lack the technical knowledge to understand fertilizers in terms of nitrogen and phosphorus nutrient values. Recall only 2% of the sample were able to name the primary plant nutrients in either DAP or urea (the only inorganic fertilizers commercially available in Ethiopia). This problem would constitute one of the market failures we had discussed in section 2.4.

While it seems clear that Ethiopian farmers in our sample were willing to pay a non-zero price for a bone-based, P-only fertilizer, it is puzzling that they did not offer higher bids for the products that included nitrogen in addition to phosphorus. Despite our efforts to explain the differences between the three fertilizers, it is possible that farmers saw all three products as being more-or-less equal, as made evident by the near identical mean WTP for each.

It is common in experimental auctions for the average WTP to be below that of the market clearing price (De Groote et al., 2011). This appears to be the case in our experiment. The mean WTP for DAP is 53.04 ETB, whereas the prevailing market value for a similar bag of DAP is 75 ETB. Interestingly, it appears that farmers were highly cognizant of the prevailing market price for DAP. We asked farmers in our survey how many kg of fertilizer they purchase every year (fertilizer consumption) and how much they spend on fertilizer every year (fertilizer spending). If we divide fertilizer spending by fertilizer consumption, we get an estimate for the farmer's estimate of the market price for fertilizer. For respondents, the mean per kg value of fertilizer is 15.09 ETB/kg with a standard deviation of 1.19 ETB. Additionally, all but two participants had purchased fertilizers at least once in the last three years, which suggests that their true max WTP is at least equal to the prevailing market price. These two facts together suggest that while our second-price auction is in theory supposed to produce an un-biased estimator of WTP, it appears that farmers were actively bidding strategically lower than their max WTP.

5.7 Regression results

As previously mentioned, we performed a random-effects GLS regression with four model specifications. The results for each of the four specifications -fertilizers only (1), cross-effects with socio-economic variables (2), cross-effects with only farming practices and fertilizer preference variables (3), and a full model with cross-effects for both socio-economic and farming and fertilizer variables (4)- are recorded in table 5.4.

In the simple model, the only regressors are binary variables for BC and MIX. In this specification, the constant term represents the WTP for the base fertilizer, DAP. We can confirm that there is no significant difference in the WTP for the three fertilizers in the experiment. While it would have been difficult to detect a difference in WTP because of the statistical power from such a small sample, it is unlikely that a lack statistical power is responsible for this result. The difference in WTP for MIX (the fertilizer with highest mean bid amount) and BC (the fertilizer with lowest mean bid amount) is 1.89 ETB. In order for such a difference to be detected with an 80% regularity, more than 3400 individuals would have to participate in auctions.

In the first expansion of the model, there are no significant cross effects. We find that as direct effects, the wealth variables, livestock holdings (TLU) and farm size, have positive coefficients, which is to be expected (Beltramo et al., 2015; De Groote et al., 2011; Morawetz et al., 2011), but they do not statistically significantly impact WTP. An additional year of education translates to an increase of 2.34 ETB for all bids and is significant at the $p < 0.05$ level, but does not lead to an increased WTP for any one fertilizer over another.

Table 5.4 WTP regression results

Model Specification		(1)		(2)		(3)		(4)	
Effects	Variable	Coeff.	S.E.	Coeff.	S.E.	Coeff.	S.E.	Coeff.	S.E.
Direct effects	Constant	53.04	2.70***	41.18	12.66***	45.05	9.37***	35.01	16.00**
	BC	-1.02	2.96	-17.21	14.18	-7.82	10.41	-32.05	18.12*
	MIX	0.86	2.96	-7.42	14.18	0.38	10.41	-13.00	18.12
	Age			-0.06	0.27			-0.01	0.27
	Education			2.34	1.04**			2.13	1.06**
	TLU			1.57	1.71			0.85	1.78
	Farm Size			1.76	3.69			1.53	3.76
	Frequency of fertilizer use					4.71	15.46	2.89	15.46
	Uses alternative fert.					10.83	5.70*	6.66	5.99
	Frequent contact with DA					2.13	7.41	3.82	7.61
	Availability premium					1.68	6.17	2.15	6.24
	Prefers imports					-5.32	7.19	-4.91	7.13
Cross eff. with BC	Age			0.38	0.30			0.45	0.31
	Education			-0.54	1.16			-0.05	1.20
	TLU			0.46	1.91			0.62	2.02
	Farm Size			1.27	4.14			3.10	4.26
	Frequency of fertilizer use					1.37	17.17	-3.88	17.51
	Uses alternative fert.					-7.90	6.33	-8.56	6.78
	Frequent contact with DA					10.71	8.23	15.11	8.62*
	Availability premium					3.93	6.85	4.52	7.06
	Prefers imports					0.32	7.99	1.98	8.08
Cross eff. with MIX	Age			0.25	0.30			0.24	0.31
	Education			-0.90	1.16			-0.23	1.20
	TLU			1.23	1.91			1.86	2.02
	Farm Size			-1.21	4.14			0.48	4.26
	Frequency of fertilizer use					7.58	17.17	3.79	17.51
	Uses alternative fert.					-15.14	6.33**	-15.89	6.78**
	Frequent contact with DA					4.12	8.23	6.37	8.62
	Availability premium					4.45	6.85	3.69	7.06
	Prefers imports					-4.60	7.99	-3.48	8.08
	Participants	118		118		118		118	
	Observations	354		354		354		354	
	R^2 *within*	0.00		0.02		0.04		0.06	
	R^2 *overall*	0.00		0.06		0.06		0.12	
	Variance due to u_i	0.40		0.37		0.38		0.36	

*sig. at p<0.1; **sig. at p<0.05; ***sig. at p<0.01

In the third specification only cross-effects for farming and fertilizer variables were added. The constant in this model represents the WTP for the base product, DAP and the base farmer, which in this case, does not use alternative fertilizers, does not place a premium on timing of fertilizer availability, prefers domestic products and does not have frequent contact with a development agent. The cross of BC and use of alternative fertilizers has a significant and negative effect on willingness-to-pay. The coefficient for the cross of MIX and alternative fertilizer use is also negative, but it is not significant.

In the full specification with cross effects for all the previous variables, education remains a significant direct effect on bid price, and the discount for BC among farmers having used alternative fertilizers is still significant. The coefficient for the crosses of alternative fertilizer was both negative and significant in both models. It may be that farmers see that BC and DAP are animal products and assume that they will have similar effects on their crops as other animal products such as manure. Manure, however, has very small amounts of nutrients compared to DAP, MIX and BC. If farmers are mistakenly associating BC and Mix with manure, it would explain the discount. This would be a reasonable assumption if we believe that farmers did not understand our discussion of nutrient values in the description of each of the three fertilizer products.

Lastly, we found the amount of variation within individuals (within r^2) to be much smaller than previous WTP research (Beltramo et al., 2015; De Groote et al., 2011; Morawetz et al., 2011). This suggests that a given farmer’s preferences and bidding behavior are influenced by factors that were not captured by the information gathered in the pre-auction survey. Getting measures for cash-in-hand, which can significantly influence individual WTP for different products in an experimental auction (Morawetz et al., 2011), is one example of a factor that was not measured in our survey. In future work, additional resources should be allocated to identifying those factors that are most likely to influence WTP and ensuring the measurement of these factors is both accurate and sufficiently precise so as to differentiate individuals within the study sample.

5.8 Results summary

We find that there is no acceptability constraint for either BC or MIX fertilizers among the sample of Ethiopian farmers participating in our experimental auctions. All bids submitted for both BC and MIX fertilizers were non-zero amounts, and the average bid for each product was significantly greater than zero. Additionally, the WTP for farmers in our trial was not significantly different for the three fertilizer products and the lack of a significant finding is not likely due to a lack of statistical power. We conclude that participants in our trial view the three fertilizer products as having more-or-less equal value, and show no preference for any one-product characteristic over another. These results indicate that there is a sizeable demand for bone char fertilizers among Ethiopian smallholders. Considering the fact that the BC fertilizer costs 33-58% less than its imported equivalent, TSP, and the MIX fertilizer costs 20-41% less than its imported equivalent, DAP, our findings suggest that a fertilizer producer could sell fertilizer at prices below the competing imported product and still generate profits. Given the number one constraint to fertilizer adoption is cost, this would both boost fertilizer adoption and offer sufficiently large margins so as to generate incentives for a start-up fertilizer industry to begin producing.

One surprising result from our research is that farmers do not apply a significant discount to BC, a sole-nutrient phosphorus fertilizer, versus DAP and MIX, despite its lack of nitrogen. While it is possible this result suggests there is significant demand for a sole-nutrient P fertilizer in Ethiopia, it is more likely that farmers in our trial lacked the technical capacity to accurately integrate fertilizer nutrient values into their WTP. This theory is supported by the fact that 98% of participants were unable to name the primary plant nutrients in either of the most commonly used fertilizers in the country (DAP and urea). Rather than discourage the developers of bone char fertilizers, however, the lack of risk aversion to novel fertilizer products despite poor information suggests that the adoption of the technology is unlikely to face major acceptability constraints, especially if dissemination efforts are made alongside investments in educating farmers on the benefits and proper use of bone char fertilizers. Given the high profit margins of producing a bone char only fertilizer as compared to a DAP fertilizer, this is an encouraging result. There may still be a market for a sole nutrient bone char based P-fertilizer, even if the federal government is not willing to integrate bone char into their national blending program. The evidence that there is no acceptability constraint for bone char fertilizer alongside the large employment bone collecting could generate, the savings with respect to foreign currency reserves and the increased food security associated with identifying and mobilizing a domestic source of P fertilizer should generate support from the government. If they are not willing to financial bolster bone char fertilizer production then it would be a wise choice to at least allow the product to enter the national value chain without restrictions.

This study was the first to use revealed preference, experimental auctions to evaluate farmer WTP for bone char fertilizer in Africa. Future research should invest additional resources in developing tools to accurately measure consumer characteristics and knowledge factors that will affect preference and WTP. Qualitative research on farmer fertilizer preferences will help guide efforts to identify such tools. Finally, it is critically important to further educate farmers on fertilizer nutrient values and fertilizer use. Without a basic technical understand of language used to discuss fertilizer quality and application, communication between fertilizer developers and their potential clients will be very difficult.

Chapter 6. Conclusion

Poor countries without P reserves, like Ethiopia, face a growing imperative to identify readily available, domestic sources of P for use as fertilizer. Not only are the world's rock phosphate supplies depleting, but too few countries control too much of the world's P reserves. Any change in supply from a major P exporting country could seriously compromise food security around the world. In this thesis we have presented a novel solution to the problem of P fertilizer availability in Ethiopia: bone char fertilizer. We have been able to show that bone residues are available in quantities that would support a profitable fertilizer industry and the work of collecting bones could offer a critical financial lifeline to at-risk communities throughout the country. Using experimental data, we have been able to show that the cost of producing bone char and getting the product into the hands of farmers costs significantly less than imported fertilizers with identical quantities of nutrients. Lastly, using experimental auctions, we have been able to show that there is no acceptability constraint to the adoption of bone char fertilizer among farmers in Ethiopia and the market price we derived from the experiments suggests that bone char fertilizers could be sold prices well above the costs of manufacturing the product.

Despite these positive results, there are many obstacles yet to be overcome if bone char fertilizer is to be widely available in Ethiopia. The Ethiopian government has complete control of the fertilizer market, from importation to marketing and financing fertilizer purchases. In order to enter the highly controlled fertilizer value chain, a bone char fertilizer producer will have to get support from the Ethiopian government. This support does not have to be financial in nature, but must manifest as an open door into the fertilizer supply chain through which bone char fertilizer can enter. It may take the form of government allowing farmers to use government credit to buy bone char fertilizers or it may take the form of integrating bone char into the new nation-wide fertilizer blending program. We feel that our research has presented a number of reasons for the government actively encourage bone char fertilizer production, from employing at-risk communities and saving vital foreign currency reserves, to boosting fertilizer adoption and food security.

Additional research must be performed in a number of key areas. Our bone collection experiment, while producing a number of useful results, did not offer a long-term picture of the bone residue supply chain. Additional research investments should be made to investigate the long-term impact of bone collecting on collector income and health. This same experiment could be used to gain a better understanding of the availability of bone residues for fertilizer production as well as generate a more accurate per kilogram market price for bone residues and a valid supply function for bone residues. The experimental auctions described in this thesis covered a limited geographical area and had a relatively small sample size, which limited our ability to identify the dimensions along which farmers made their bidding decisions. Future experiments should expand across the country to ensure that acceptability of bone char is not a regional phenomenon. Additionally, the large sample sizes that such a study would produce, will give researchers the statistical power to integrate different treatments into the trial, such marketing and post-harvest WTP experiments.

Lastly, the problems with power, scarcity and price volatility in the world phosphorus market does is not a problem that is unique to Ethiopia, but represent a challenge that must be addressed in nearly every country around the world. This thesis lays forward the steps that are needed to investigate bone residues as source of alternative P-fertilizer in the developing world, and the innovation will likely be applicable in other African countries. Indeed, many countries surrounding Ethiopia also have no mineable P reserves (*i.e.* Sudan, South Sudan, Kenya, Uganda and Tanzania) and have over 10 million head of cattle. Bone char fertilizer may be a viable means of improving phosphorus fertilizer availability and food security not only in Ethiopia but also in countries across Africa.

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APPENDIX A

Granulated Bone Char Laboratory Results

THORNTON LABORATORIES
TESTING & INSPECTION SERVICES, INC.

1145 E. Cass St, Tampa, FL 33602
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16-Sep-2016
Page 1 of 1

Report For: Cornell University
306 Tower Rd.
918 Bradfield Hall
Ithaca, NY 14853
Attn: Kelly Hanley

Sample Identification:

Bone Char Fertilizer, Sample #1
ID: Pelletized Bone Char w/ Binding Agents (Molasses)

Date Received: 30-Aug-2016

Laboratory Number: 397624

CERTIFICATE OF ANALYSIS
OFFICIAL ANALYSIS *

Method	Parameter	Result	Units
AOAC 958.01			
	Phosphate, Total (P2O5)	31.50	%
AOAC 977.01,958.01			
	Phosphate, Water Soluble (P2O5)	0.20	%
AOAC 2006.03(mod)			
	Calcium (Ca)	28.91	%
	Iron (Fe)	0.21	%
	Magnesium, (Mg)	0.55	%
	Manganese (Mn)	0.01	%
	Sodium (Na)	0.62	%
AOAC 955.01			
	Calcium Carbonate Equivalent	12.85	%
NFSA 1980			
	pH Value	7.13	
EU 2003/2003			
	Phosphate (P2O5), Soluble in 2% Citric Acid	25.33	%

* Average of closely agreeing
duplicate determinations.

THORNTON LABORATORIES
Steve Fickett, III

Thornton Laboratories Testing & Inspection Services, Inc. responsibility for the above analysis, opinions, or interpretations is limited to the invoice amount.

THORNTON LABORATORIES
TESTING & INSPECTION SERVICES, INC.

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12-Sep-2016

Report For: Cornell University
306 Tower Rd.
918 Bradfield Hall
Ithaca, NY 14853
Attn: Kelly Hanley

Sample Identification:

Bone Char Fertilizer, Sample #1
ID: Pelletized Bone Char w/ Binding Agents (Molasses)

Date Received: 30-Aug-2016

Laboratory Number: 397624A

CERTIFICATE OF ANALYSIS

Method	Parameter	Result	Units	Detection Limit-	Analysis Date/Analyst
EPA 6010					
	Arsenic (As), Total	< 0.98	mg/Kg	0.98	09-08-16 *
	Cadmium (Cd), Total	< 0.1	mg/Kg	0.01	09-06-16 DS
	Chromium (Cr), Total	5.5	mg/Kg	0.01	09-06-16 DS
	Cobalt (Co), Total	< 0.1	mg/Kg	0.01	09-06-16 DS
	Copper (Cu), Total	1.2	mg/Kg	0.01	09-06-16 DS
	Lead (Pb), Total	< 1	mg/Kg	0.01	09-06-16 DS
EPA 7471					
	Mercury (Hg), Total	< 0.01	mg/Kg	0.01	09-02-16 *
EPA 6010					
	Molybdenum (Mo), Total	< 0.3	mg/Kg	0.01	09-06-16 DS
	Nickel (Ni), Total	2.3	mg/Kg	0.01	09-06-16 DS
	Zinc (Zn), Total	116	mg/Kg	0.01	09-06-16 DS
	Selenium (Se), Total	< 0.74	mg/Kg	0.74	09-07-16 *
EPA 3050B					
	Digestion/Preparation for Analysis			1.0269-100	09-02-16 SR

* *Analysis performed by Pace Analytical [#E84809].*

THORNTON LABORATORIES
Steve Fickett, III

APPENDIX B

Entrepreneurship Training Outline

Module 1: General overview of Entrepreneurship

- Discussion and experience sharing
- Introduction to entrepreneurship
- Principles of entrepreneurship
- Classification and Types of entrepreneurship (what to do, how to collect bones, methods of collecting bone, benefit of collecting bone, where to find the bone ….)
- Discussion on how could once find bone
- What is SMEs? And concept
- Function and role of entrepreneurship
- Exercise

Module 2: how to become an entrepreneur

- Discussion
- Employment and self employment
- Advantage and disadvantages of self employment
- Discussion
- How to generate income from collecting bone (collect more earn more money…)
- Characteristics of entrepreneur
- Assess once own potential by collecting bone
- Exercise

Module 3: organizing an enterprise

- Discussion
- The role of business in economy
- Success factors for setting up SMEs
- How to work with others to collect bone
- Location
- How to manage business
- Identifying customers
- Customer handling
- Exercise

Module 4: How to operate an enterprise

- Human recourse management
- Hiring and managing of workers to collect bone
- Discussion
- Time management (how much kg of bone collected per day,….)
- Profit calculation (price of collected bone, …)
- How to deal with suppliers for collecting bone
- Discussion
- Preparing financial statement
- Negotiation and customer service
- Risk management (safety for collecting the bone, …)
- Exercise

APPENDIX C

Granulation of Bone Char Fertilizer: An Evaluation of Process Parameters and Their Effect on Granule Strength

1. Introduction

The world supply of phosphorus (P), a primary plant nutrient, is running out (Beardsley, 2011). As international prices for P fertilizer become increasingly volatile, poor countries with no mineable P reserves will be pushed out of the market (Dana Cordell, Drangert, & White, 2009). It is vital, therefore, that developing countries leverage local sources of P to bolster fertilizer supplies and food security (D. Cordell, Rosemarin, Schröder, & Smit, 2011).

In Ethiopia, the country with the largest animal herd in Sub-Saharan Africa, there is growing interest in bone char as a local and sustainable source of P fertilizer (A. Simons, Solomon, Chibssa, Blalock, & Lehmann, 2014). Bone char is produced via pyrolysis, a process in which bone meal (a slaughterhouse waste) is placed inside a chamber with limited oxygen and heated in excess of 400° C. Pyrolysis sterilizes the product, preventing the transmission diseases associated with raw animal products (Warren, Robinson, & Someus, 2009) and increases the concentration of desirable nutrients like P and calcium (Ca). Bone char is typically 14 - 16% elemental P and approximately 30% Ca (Zwetsloot, Lehmann, & Solomon, 2015). If enough bone residues were to be diverted to bone char fertilizer production, phosphorus fertilizer imports could be reduced by 28-58% (A. Simons et al., 2014).

The potential impact of introducing bone char fertilizer to Ethiopia is promising, but unprocessed bone char has physical properties that reduce its efficiency, usability and marketability as a fertilizer. The locally rendered bone (bone meal) in Ethiopia that is used to produce bone char has a very wide particle size distribution, ranging from less than 1 mm to greater than 10 cm. Wide particle size distributions can lead to uneven spreading during application, which in turn, can increase nutrient losses, reduce fertilizer efficiency and negatively impact profit margins (Dilz & van Brakel, 1985). Additionally, the mass to surface ratio is an important determinant of how quickly nutrients become available to plants after application (Klock & Taber, 1996; Vassilev, Martos, Mendes, Martos, & Vassileva, 2013). The larger particles in unprocessed bone char negatively affect the timing and predictability of P-availability in the soil after application. One potential solution would be to grind the bone char into a fine powder. Grinding the bone would reduce the surface to mass ratio of the bone char particles improving P dissolution and availability but handling and applying fertilizers in powdered form can be immensely difficult (Albert & Langford, 1991; Reynolds, Fu, Cheong, Hounslow, & Salman, 2005). We propose to overcome these challenges presented by developing methods for converting the powdered bone char into durable fertilizer granules.

Granulation is defined as the “size enlargement process of the agglomeration of smaller particles together into larger, semi-permanent aggregates” (Mangwandi, Albadarin, JiangTao, Allen, & Walker, 2014). Granulating fertilizer significantly increases it’s value, reduces environmental hazards and improves handling properties (Albert & Langford, 1991; Mangwandi, Albadarin, Al-Muhtaseb, Allen, & Walker, 2013; Mangwandi et al., 2014; Reynolds et al., 2005). The production of quality granules can be difficult to control and optimize (Adetayo, Litster, Pratsinis, & Ennis, 1995). Methods for fabricating granules from powdered bone char have never been explored, and little work has been done on materials with physical characteristics similar to that of bone char (Walker, Holland, Ahmad, Fox, & Kells, 2000).

One common method for producing granules is pan granulation or pan pelletization (Mangwandi et al., 2013). Pan granulation consists of spraying a binding solution onto a cascading bed of particles, which "snowball", accumulating mass until they are ejected from the granulation unit (Meline, McCamy, Graham, & Sloan, 1968). In such a system, granule size, strength and durability can be influenced by "playing" with a few production parameters (Irshad, Sharif, Khan, & Rizvi, 2010).

Little work has been done to determine the effects of various process parameters on the final quality of fertilizer granules (Rahmanian, Naji, & Ghadiri, 2011). Papers that have explored the impact of process parameters focus on granule structure (Walker et al., 2000; Zafari & Kianmehr, 2012), microscopic factors which in turn impact the granule static crush strength (Walker et al., 1997; Walker, Moursy, Holland, & Ahmad, 2003), size distribution (Adetayo et al., 1995), granule porosity (Utsumi et al., 2001) and surface roughness (Bortzmeyer & Goimard, 1996). There is a need to investigate the effect of process parameters on granule quality. If the research is to be appropriate and useful for fertilizer producers in Ethiopia, as well as the rest of the developing world, the findings should be presented in as simple a way as possible. Lastly, it is important to optimize the granulation processes, and a prerequisite to optimizing the process is generating a model to predict a given granule characteristic "as a function of process parameters" (Adetayo et al., 1995).

In this study we produce various batches bone char granules by systematically and incrementally influencing various process parameters. We investigate the usefulness of various tests of granule quality and discuss the implications of their outcomes for the adoption of bone char fertilizer in Ethiopia. Lastly, we propose three models, which can be used to identify the relationships between production parameters and desirable granule characteristics.

2 Materials and Methods

2.1 Bone Char Preparation

The bone char we used for pelletization was produced in a wood-fueled, barrel-type pyrolysis kiln. The temperature conditions during pyrolysis were measured with a voltmeter and J-type thermocouple suspended within the pyrolysis chamber. The max exposure temperature for the bone char used for pelletization ranged from 450-650°C and yields, as percentage of initial bone mass, ranged from 61-79%. The samples were ground into a powder using a Fritsch Pulverisette 19 Universal Cutting Mill. The rotor used for grinding had straight cutting edges and fixed knives. The sieve cassette had trapezoidal perforations with a diameter of .025 mm

2.2 Binder Preparations and Sprayer Calibration

The gelatinized starch-binder solution was prepared by adding 50g food grade cornstarch (Safa Brand Corn Flour) to 400 ml of room-temperature water inside a 1 L beaker. The solution was agitated, placed on a hotplate and stirred continuously until a clear gel formed. Once cooled, the starch gel was combined with 600 ml of water in a blender and agitated until a uniform solution formed. The final product was a 5% (by weight) starch solution. The binder solution applied during granulation was 5% cornstarch for all data included in this paper.

The binder solution was then added to a 32 oz SprayMaster brand pump sprayer (Delta Industries; Prussia, Pennsylvania). The number of pumps per minute regulates the amount of binder in the final granule. The proper number of pumps per minute was determined by the desired binder composition of the final granule, the addition rate of bone char fines (grams/minute), the concentration of the binder solution (grams/liter) and the volume of binder released with each pump of the sprayer[48]. In our experiment, the average volume per spray was 2.6 mL.

The equation for determining pumps per minute is below:

$$\text{sprays per minute} = \left(\frac{(\%bfp)(bc)}{(bcomp)(vol)}\right) \div 100 \qquad \text{Eq. 1}$$

%fp – percent binder desired in final product
bc - kilograms of bone char fines added to disk pelletizer per minute (g/min)
vol - volume per pump (L/spray)
bcomp - concentration of binder solution (g/L)

2.3 Granulation, Sieving and Drying

The granules were produced inside a shallow disk-type pelletizer with a 14” diameter pan and 3” pan depth (Mars Mineral, model DP-14 Laboratory Pelletizer, see appendix A). A single

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[48] The pump sprayer is hand-powered and the spray output (volume of binder solution released with each pump of the sprayer) is different for each technician performing the pelletization. The spray output was measured by inserting the tip of the sprayer into a graduated cylinder and holding the sprayer upright, pumped 10x. The volume of the binder solution within the graduated cylinder is recorded. The process is repeated 10x and the average volume per spray is then calculated.

researcher operated the pelletizer during the production of all granule samples included in this paper.

Prior to starting the pelletizer, a lab technician set the pan angle (defined as the angle between rear wall of pelletizer pan and horizontal) and pan rotation speed at the desired specifications. Bone char powder was added at a rate of 86 g / minute for all samples produced, which is ~95% of the manufacturer's stated production capacity of the DP-14 model pelletizer. Binder solution was sprayed directly to the bone char powder within the rotating disk. The amount of binder in the final product was modified by adjusting the number of sprayer pumps per minute (see equation 1 above). Each pump applied an average of 2.6 mL of 5% binder solution. Separate alarms indicated to the researcher when additional bone char was to be added to the pelletizer and when to apply binder.

The size distribution of granules for each batch was determined using a series of three sieves. The size of the sieves were 2.36, 4.0 and 8.0 mm[49]. To prevent granule breakage, the stacked sieves were gently agitated by hand until no further changes occurred in the distribution of the granules.

---

[49] When measuring granule size distribution, it is typical to use more than 3 sieve sizes. The European standard procedure for test sieving (EN1235:1995) is the most commonly used procedure seen in the literature and requires 7 sieves ((D.L. Antille, Tyrrel, Godwin, & others, 2013; Miserque & Pirard, 2004; Pirard, Miserque, & Chapeau, n.d.). The European fertilizer blenders association recommends that these 7 sieves have apertures of 1 , 2.5 , 2.8 , 3.15 , 3.55 , 4 , 5mm respectively(("European Fertilizer Blenders Association: Granulation," n.d.). Since there is no globally accepted procedure for measuring the size distribution of granules, the apertures and number of the sieves can be different across studies (Allaire & Parent, 2003; D.L. Antille, Sakrabani, Tyrrel, Le, & Godwin, 2013; D.L. Antille, Tyrrel, et al., 2013; Chok, Grafton, Mills, & Yule, 2014). Statistical descriptions of fertilizer granule size distribution require that 84-95% of the mass of the sample pass through the sieve with the largest aperture. The IFDC suggests selecting "a series of sieves of such sizes that… if possible, no one sieve retains more than 50% of the entire sample, no more than 10% of the sample remains on the top sieve, and no more than 10% of the sample passes the bottom sieve" (Rutland, 1986).

Green granules (undried) between 2.36 and 8.0 mm in diameter were mixed and 200g samples were placed on 6 separate steel trays. One tray was left on a laboratory bench to air-dry for at least 24 hours. The remaining five trays were transferred to a drying oven set at 105*C (Reza, Lynam, Vasquez, & Coronella, 2012) and subject to drying times of 15, 30, 45, 60 and 120 minutes, respectively. Once removed the pellets were left on the laboratory bench to cool until quality testing took place the following day.

2.4 Repeated impact test (RIT)

Ten granules were randomly selected from the samples corresponding with each drying time. Each granule was dropped repeatedly from a height of 18" (46cm) onto a solid metal plate until significant breakage occurred (Veverka & Hinkle, 2001a). Negating air resistance, which unlikely to be an important factor over such a short drop distance, the impact velocity of each drop was ~3m/s. The number of drops prior to breakage was recorded and an average number of drops for the ten granules from each sample was calculated. It was necessary to impose an upper bound on the number of drops. We adopted the method from Albert and Langford 1991 in which a 50-drop maximum was imposed. A typical granule must survive 10 drops before considered strong enough for handling (Albert & Langford, 1991).

The repeated impact test represents the granules' ability to resist breakage during processing (dropping conveyor belt, *etc.*) and handling (mechanical spreaders, especially fan-type spreaders)(IFDC & UNDP, 1998). The RIT described above is typically used in the pelletizing/agglomerizing industry during initial testing stages of pelletizing novel materials (C. Taylor, Mars Mineral Laboratory Manager, personal communication, June 24 2016)[50].

2.5 Sieve Attrition Test

A 100g sample was placed inside a 2.0 mm sieve with a cover and catch plate below. The sieve was placed onto a shaker set on high for 5 minutes. After being agitated, the mass of the particles passing though the sieve was considered loss due to attrition.

$$\text{Percent Attrition} = \left(\frac{\text{loss due to attrition (g)}}{\text{original sample (100g)}} \right) \times 100 \qquad \text{Eq. 2}$$

Granules are expected to withstand significant stress of handling without damage but must disperse quickly upon final application (Bortzmeyer & Goimard, 1996; Utsumi et al., 2001). This attrition test is the optimum test for evaluating granule friability, which acts as a proxy for these characteristics and may be better than static granule strength tests, such as the crush test (Utsumi et al., 2001). Traditional sieve attrition tests, such as the method described in the International Fertilizer Development Center (IFDC) fertilizer manual, are conducted with a sieve and metal or plastic balls that enhance the attrition rate during agitation (Bemrose & Bridgwater, 1987;

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[50] Single particle impact test tests are the traditional method for studying breakage of granules (Antonyuk, Khanal, Tomas, Heinrich, & Mörl, 2006; Antonyuk, Palis, & Heinrich, 2011; Antonyuk, Tomas, Heinrich, & Mörl, 2005; Mishra & Thornton, 2001; Salman, Fu, Gorham, & Hounslow, 2003). Impact velocity of the granule can either be controlled by dropping granules from different heights (Mishra & Thornton, 2001; Veverka & Hinkle, 2001b), pneumatic, magnetic or mechanical propulsion ((Antonyuk et al., 2006, 2011, 2005; Jovanović et al., 2016; Salman et al., 2003; Veverka & Hinkle, 2001b) or an oscillating chamber (Pitchumani, Strien, Meesters, Schaafsma, & Scarlett, 2004). The impact velocity for single particle, single impact tests are typically quite high, ranging from 5.0 – 25.0 m/s. Since particles are expected to break at their weakest points, using multiple drops allows us to use impact velocities significantly lower than a single drop test (Pitchumani et al., 2004). For this reason, the relatively low impact velocity of 3 m/s is appropriate.

Rutland, 1986; Utsumi et al., 2001; Utsumi, Hirano, Mori, Tsubaki, & Maeda, 2002). Utsumi *et al.* (2002) suggests that using such enhancement methods "are not desirable because the enhancing balls complicate attrition". Botzmeyer & Goimard (1996) found that the enhanced attrition test and attrition test without enhancing balls "gave the same ranks for attrition rates" for granules made from various materials. The source for the methodology used in this paper can be found in Jovanovic *et al.* (2016) and Veverka & Hinkle (2001). Typical values range from 2-3% attrition and should not exceed 5% (Albert & Langford, 1991).

2.6 Bagged Impact Test

A 100g sample was placed in a polyethylene bag and tied shut. The bag was dropped ten times from a height of 1.5m onto a solid metal plate. After the 10 drops, the sample was placed onto a 2.36 mm sieve and gently shaken. The mass of the particles passing though the sieve was considered loss due to attrition.

The bagged impact test is an indication of the mechanical strength of granules, particularly when fan-type spreaders are used and when bags of fertilizer are dropped during handling and transport. This test combines the stresses of previous two tests: abrasion between granules and impact upon striking the metal plate. The methodology is taken from Jovanovic *et al.* (2016), except that granules are dropped from 1.5 m rather than .457 m[51].

[51] The method is similar to the methodology from the IFDC testing manual, in which a 100g sample is dropped from a height of 10.7 m onto a metal plate (Rutland, 1986). The facilities required to conduct the tests in the IFDC manual were not available in Jimma, Ethiopia. We believe that the act of repeated drops will generate similar results to that of a single drop from a greater height.

2.7 Size Guide Number (SGN)

The SGN is the median or geometric mean of the granules in a given sample, corresponding to $P(X<x)=0.5$ where X is the granule size and P is the percentage of granules, by mass, passing through sieve size x (Allaire & Parent, 2003). The particle size (in millimeters) at $P(X<x)=0.5$ is multiplied by 100 and rounded to the nearest 5 (Rutland, 1986).

The size guide number is an important metric for determining whether two fertilizers are suitable to be mixed. If the difference between the SGN of, say, granulated bone char and urea is greater than 10, the fertilizer will separate during handling and processing with smaller particles settling to the bottom (Rutland, 1986).

In the United States, granular fertilizers typically have an SGN between 100 and 340 (IFDC & UNDP, 1998). In Europe, SGN is 300-350 ("European Fertilizer Blenders Association: Granulation," n.d.). An SGN as high as 450 would be acceptable for most mechanical applications (Pirard, Miserque, & Chapeau, n.d.).

2.8 Granulometric Spread Index (GSI)

The GSI is the measure of the spread of the size distribution for a granulated fertilizer outlined in the EU standard EN 1245:1995 ("European Fertilizer Blenders Association: Granulation," n.d.). Calculating the GSI requires three percentiles obtained during sieving, $P(X<x)=0.14$,

P(X<x)=0.5 and P(X<x)=0.86 represented as d_{14} , d_{50} , and $d_{86,}$ respectively (D.L. Antille, Tyrrel, Godwin, & others, 2013). The equation for GSI is:

$$GSI = \left(\frac{d_{84} - d_{16}}{2 \times d_{50}} \right) \times 100$$ Eq. 3

The GSI provides an indication of the likelihood that granules will undergo segregation during transport and handling (D.L. Antille, Sakrabani, Tyrrel, Le, & Godwin, 2013). A lower GSI is considered desireable. Just as in mixing two fertilizers with different SGNs, fertilizers with a GSI that is too large will present handling problems. Miserque & Pirard (2004) indicate that a GSI < 10 is necessary to have segregation that is essentially zero. The European Fertilizer Blenders Association website on granulation states that GSI should not be greater than 18. Pirard, Miserque and Chapeau n.d., suggest a GSI between 10 and 50 is acceptable.

2.9 Uniformity Index (UI)

The uniformity index, like GSI, is a measure of the spread of the size distribution for a fertilizer. The UI is the standard measure for spread in the United States *(Allaire & Parent, 2003).* The UI requires two percentiles be obtained from sieving: d_{95}, *P(X<x)=.95 ;* d_{10}, *P(X<x)=.10*. The equation for UI is:

$$UI = \left(\frac{d_{10}}{d_{95}} \right) \times 100$$ Eq. 4

A higher UI is considered desirable, and the consequences of a low UI are the same as those for a GSI that is too high. Henderson 2014 suggests that a UI >50 is excellent, UI=41-50 is acceptable, UI=31-40 is questionable and UI≤30 is unacceptable. Chok *et al.* (2014) give an acceptable UI range of 20-60, however, in a survey of fertilizer in New Zealand the authors found that only 47% of phosphate fertilizers would meet the minimum requirement of UI=20 and only 26% would meet the UI>30 minimum suggested by Henderson 2014.

2.10 Percent Useful Granules

For the purpose of this work, we have determined that useful granules are those within the target range a of 2.36-8mm (diameter). The percentage of useful granules is a measure of efficiency because any particles outside this target range would have to be removed, crushed and reintroduced into the pelletizer (Ghasemi, Kianmehr, Mirzabe, & Abooali, 2013; Mangwandi, Albadarin, Al-Muhtaseb, Allen, & Walker, 2013). The equation for percent useful pellets is:

$$\text{Percent Useful Granules} = \left(\frac{M_{target}}{M_{total}}\right) \times 100 \qquad \text{Eq. 5}$$

where M_{target} is the mass of useful granules *vis-à-vis* those between 2.36 and 8 mm in diameter and M_{total} is the total yield from the batch of granules.

Typical values for useful granules produced in a pan granulation system is between 50-75% (Albert & Langford, 1991). Our useful granule range, however, is much broader than applications, so we will set our minimum quality standard for efficiency at 90% yield of useful granules, which is equal to the yield of a highly efficient granulation system (Fogel, 1960). Lastly, we justify our definition of useful granules over such a broad range because we believe that the negative effects of a wide granule size distribution on fertilizer use efficiency (Dilz & van Brakel, 1985; Horrell, Metherell, Ford, & Doscher, 1999) will be mitigated by the fact that virtually all fertilizers are hand-broadcasted in Ethiopia (Negatu, Mwangi, & Tesemma, 1994). Most of the problems created by wide granule size distribution is related to the use of mechanized fertilizer spreaders (Miserque & Pirard, 2004, 2004; Rutland, 1986).

3. Results & Discussion

3.1 Useful Granules Results

A total of 36 batches of granules were produced for which the percentage of useful granules could be calculated. For this paper, we defined useful granules as those between 2.36 and 8mm, which will serve as a measure of efficiency for our system. In a more complicated pelletization system oversized and undersized granules would be screened, crushed and reintroduced to the system until nearly 100% of the original material is converted into useful granules (Albert & Langford, 1991; Ghasemi et al., 2013; Mangwandi et al., 2013).

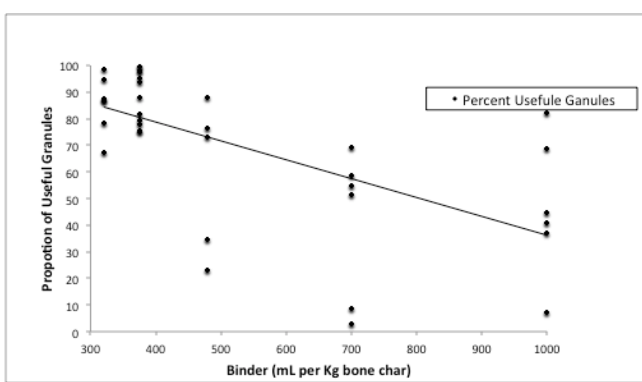

Figure 1. Yield of useful granules (2.36-8.0mm) and the volume of binder applied for each kilogram of bonechar

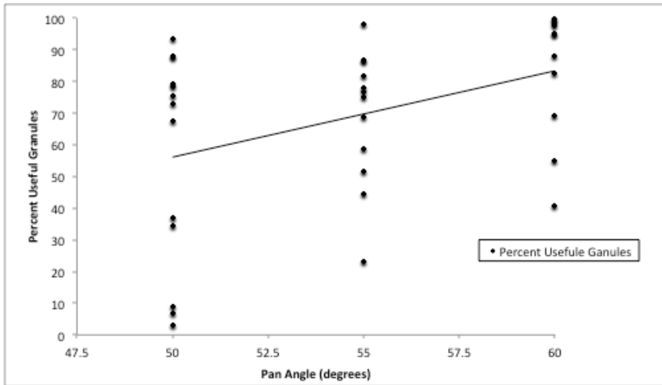

Figure 3- Yield of useful granules (2.36-8.0mm) and the pelletizer pan angle

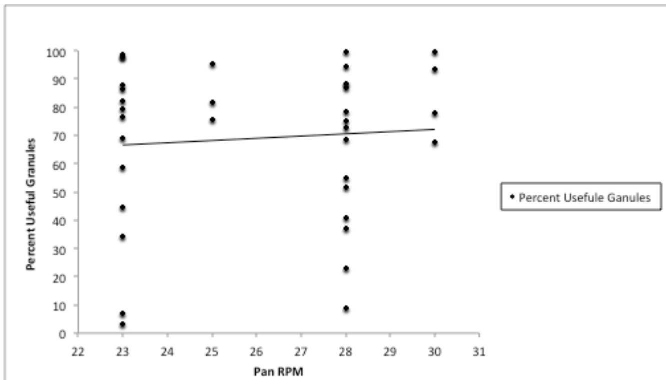

Figure 4-Yield of useful granules (2.36-8.0mm) and RPM of pelletizer pan

From figure 1, it appears that the yield of useful granules may be negatively affected by the ratio of binder solution (mL) to bone char (kg). Most related granulation research is conducted on soluble materials, and the effect of binder viscosity rather than dosage was investigated (Mangwandi et al., 2013; Pujara, 2007; Walker, Holland, Ahmad, Fox, & Kells, 2000). In Jovanovic *et al.* (2016), increased binder solution led to larger granules, which in turn, decreased the yield of desirable granules. Pujara (2007) corroborated the effect of binder dosage on granule size. Fogel (1960) reported that there is a linear relationship between particle size and binder solution that has a rate of change that is approximately .5mm/1% binder and a polynomial relationship between binder dosage and useful granules. Irshad *et al.* (2010) found binder increased the proportion of useful granules up to a point, after which, the proportion of useful granules decreased.

Figure 2 indicates that the proportion of useful granules produced may increase with the pan angle. Fogel (1960) found that pan angle did not affect granule production rate, but did not report results for granules size distribution. Delwel and Veer (1978) reported that smaller angles of inclination produced larger granules, which would support our finding, since the majority of granules outside the range of useful granules are too large rather than too small.

Ghasemi *et al.* (2013) found that increased rotation speed improved the yield of useful granules by decreasing the size of granules. Irshad *et al.* (2010) found that pan RPM increased useful granules up to a point, after which, useful granule yield began to decline. However, in our setting the effect of RPM on the yield of useful granules changes little (Figure 3)[52].

3.2 Size Guide Number, Uniformity Index and Granulometric Spread Index Results

A fertilizer should have an SGN of 100-400 in order to function normally during application, mixing and transportation (Diogenes Luis Antille, Godwin, & others, 2013). We were able to obtain an SGN for 29 of the 36 granule samples. The seven samples for which an SGN could not be calculated had more than 50% retention of granules at the largest sieve aperture. The majority of the granules produced (25 of 36 samples) in our experiment have an SGN of 800, with only 4 of the 36 batches producing granules with an SGN of 400. An SGN of 400 is the upper bound for

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[52] Walker *et al.* (2000) suggest that optimal rotation speed can be calculated from the equation $N_{FR} = 42.4\ D^{-0.5}$, where N is the optimal rotation speed and D is the diameter of granulation drum. Using this equation, the optimal rotation speed for the DP-14 unit used in these experiments would be ~70 RPM.

commercial fertilizers in Europe and the United States (Allaire & Parent, 2003; Diogenes Luis Antille, Godwin, et al., 2013; Chok, Grafton, Mills, & Yule, 2014). The production parameters for those samples with an SGN of 400 is reported in table 1.

Table 1. Production parameters of batches yielding granules with SGN of 400

Batch	Binder (%)	Pan RPM	Pan Angle	Yield Useful Granules (%)
A	1.6	23	55	86.5
B	1.6	28	55	86.8
C	1.88	23	55	97.9
D	1.88	30	60	99.4

The results of our samples indicate that a mixing granulated bone char with other fertilizers presents a significant challenge. In order to mix two fertilizers, their SGNs should not differ by more than 20 (Rutland, 1986). While an SGN of 400 is the upper bound for commercial fertilizers and some of our samples had and SGN of 400, most fertilizers have a much smaller SGN (Allaire & Parent, 2003; Chok et al., 2014; "European Fertilizer Blenders Association: Granulation," n.d.).

The issue of mixing is relevant in the Ethiopian context for two important reasons. The first is that diammonium phosphate (18-46-0) and urea (46-0-0) are the most commonly used fertilizers in Ethiopia. There are no widely available sole-nutrient phosphorus fertilizers in Ethiopia (Rashid et al., 2013), and there has been no research on the marketability of such a product[53]. If there is no market for a sole-nutrient phosphorus fertilizer, it may be necessary to mix granulated bone char with urea (a sole-nutrient nitrogen fertilizer) so that it has the N:P ratio as DAP. Such

[53] We are currently conducting willingness-to-pay experiments with both granulated bone char and granulated bone char mixed with urea. Preliminary evidence suggests that there would be significant demand for a sole-nutrient phosphorus fertilizer if it were made available.

a mixture may maximize the familiarity of the product and thus reduce the risk aversion and subsequent discount associated with a new good about which an individual lacks information (Heffernan & Ariga, 2012; Kalish, 1985). Alternatively, it may be possible to mix bone char with ground urea to produce a single granule containing both nitrogen and phosphorus. Additional research should be done exploring this possibility. The second is that the government of Ethiopia intends to produce fertilizer blends at a national scale (ATA, 2014). Therefore it makes sense to create the granulated bone char to be compatible for blending with other products.

Table 2. Results for granulometric spread index

GSI Value Range	0-18	19-30	31-50	Unknown
Number of samples falling within range	4	7	4	21

We were able to calculate the granulometric spread index (GSI) for 15 of the 36 samples. Samples for which the GSI was not calculated had greater than 16% of the sample retained on the sieve with the greatest aperture (see Equation 3). While only 4 samples meet the European Fertilizer Blender Association standard of GSI ≤ 18, it is more appropriate to adopt the standard of GS ≤ 50 proposed by Pirard, Miserque and Chapeau n.d, since Ethiopian farmers largely do not use the high precision equipment that is more commonplace in Europe and other advanced economies.

The uniformity index (UI) was calculated for 7 samples. Among those samples, th UI was calculated to be 29.5, which is below the minimum value laid forth by Henderson 2014 but within the acceptable range presented by Chok *et al.* 2014.

3.3 Repeated Impact Test Results

There were a total of 216 observations for the repeated impact test (36 batches were dried for 6 different lengths of time). Only two samples were below the minimum quality threshold of 10 drops before breakage. This indicates that the 10-drop threshold is not a sufficiently discerning cut-off for granule strength so as to be useful in differentiating the durability between fertilizer granules.

Furthermore, of the 2160 granules dropped, 1353 reached the 50-drop maximum. The upper bound truncation (more than 50% of granules tested) makes it difficult to differentiate between which production parameters influence granule strength and the number of drops required to break granules is so large and the work is so time consuming that our method of RIT is neither practical or economical. The lack of a well-defined and functional quality threshold, the time required to perform the test and the problems associated with upper bound truncation make this test a poor choice for measuring granule quality of bone char. Given the problems presented by the repeated impact test, we have decided to focus analysis on the attrition test (sieve test) and bagged drop test.

Table 3. Summary statistics for granule physical characteristics and quality tests

Test/Characteristic	**Obs.**	**Mean**	**Std Dev.**	**Min.**	**Max**	**Percent at quality standard**
Useful Granules	36	68.98%	27.75	3.07%	99.72%	22.22%
RIT (drop test)	216	40.04	11.84	8.80	50.00	99.07%
Attrition Test	180	6.65%	17.17	0.50%	24.00%	48.89%
Bagged Drop	180	12.23%	7.77	1.00%	36.00%	18.89%

3.4 Bagged Drop Test and Sieve Attrition Test Results

The literature suggests that three factors may be acting to influence granule strength within our system: granule moisture content (influenced by drying time), binder content as percent of the final mass, and residency time (controlled in our system by changing pan angle). Previous work has found that increased drying time, which reduces the moisture content in granules, increases the hardness and strength of granules (Hardesty & Ross, 1938). Attrition behavior of granules, however, is not necessarily related to hardness (Bortzmeyer & Goimard, 1996). Residency time, which we have observed is influenced by pan angle (decreased pan angle increases residency time), positively influences granule strength, the underlying cause of which is an increase in granule density (Rahmanian, Naji, & Ghadiri, 2011). Jovanovic *et al.* (2016) found that increasing binder as a percent of the final product increases granule strength up to 5% binder, after which granule strength declined. The same study similar results for attrition.

There were a total of 180 observations of the bagged drop test. Of these 180 observations, 34 samples (18.9%) met the quality threshold of no more than 5% loss due to attrition. As to the factors that influence attrition, it appears that increasing drying time may reduce the loss due to attrition in bagged drop tests. This finding agrees with the existing literature. The exact nature of the relationship (linear, polynomial *etc.*) will be explored in the modeling section.

Similar to the bagged drop test, there were 36 batches of granules produced and samples from each batch was subjected to 5 drying times (15, 30, 45, 60, 120), resulting in 180 total

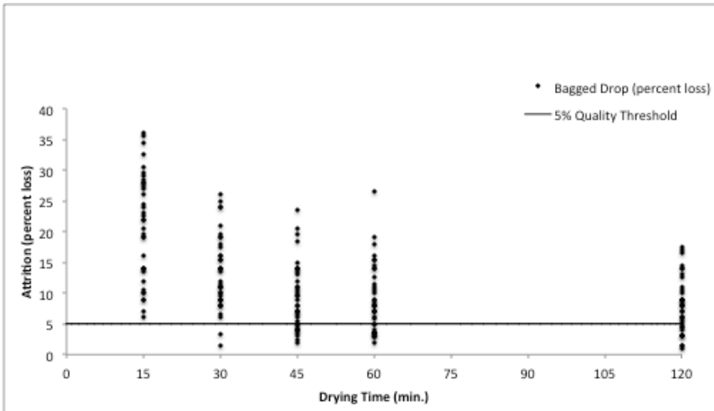


Figure 5- Drying time and attrition in bagged drop test

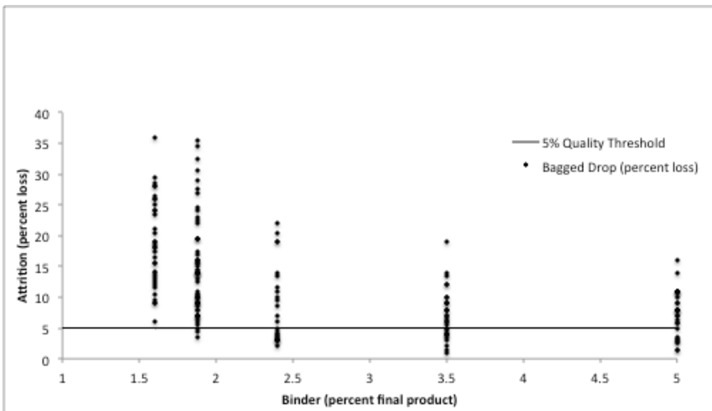


Figure 6- Binder as percent of final product and attrition in bagged drop test

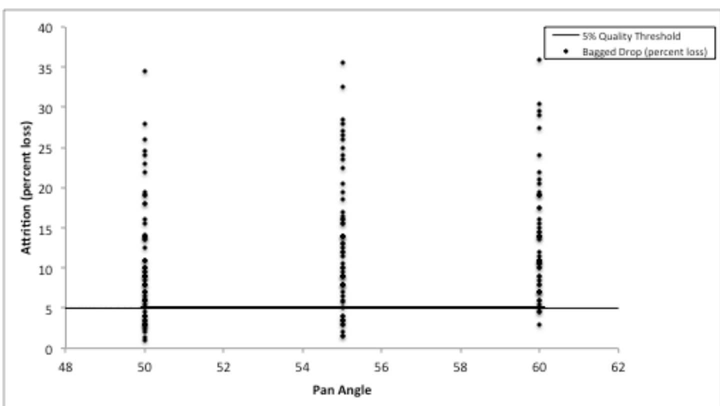


Figure 7- Pan angle (as proxy for retention time) and attrition in bagged drop test

observations. Approximately 49% of samples achieved the minimum quality standard of no more than 5% loss due to attrition. This suggests that the 5% quality threshold does not differentiate between high quality and low quality granules as aggressively as the bagged drop test in which only 18.9% of samples met the minimum quality threshold. The initial results for the sieve test are reported in figures 7-9.

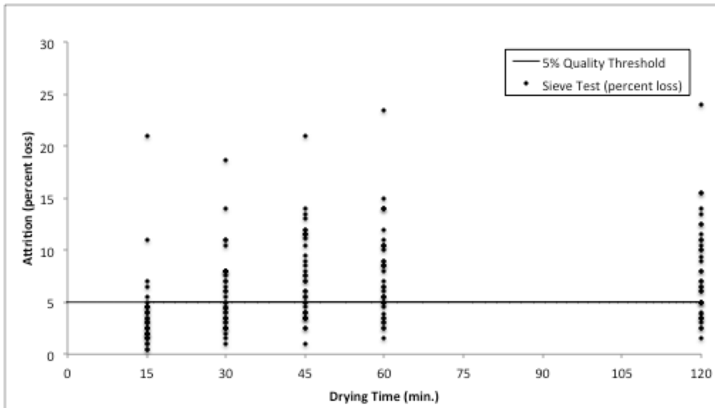


Figure 8 - Drying time and attrition in sieve test

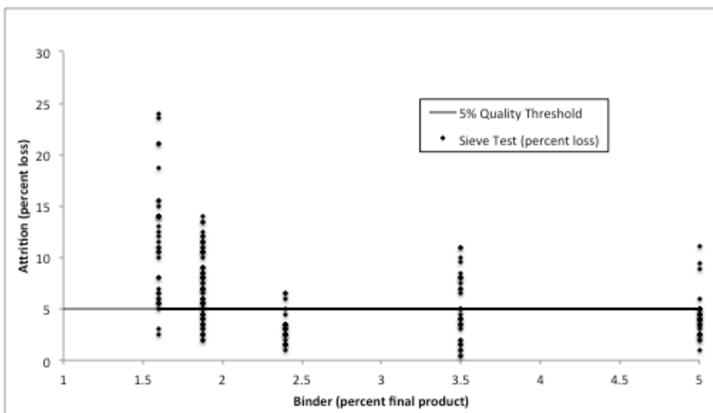


Figure 9- Binder (as percent mass of final product) and attrition in sieve test

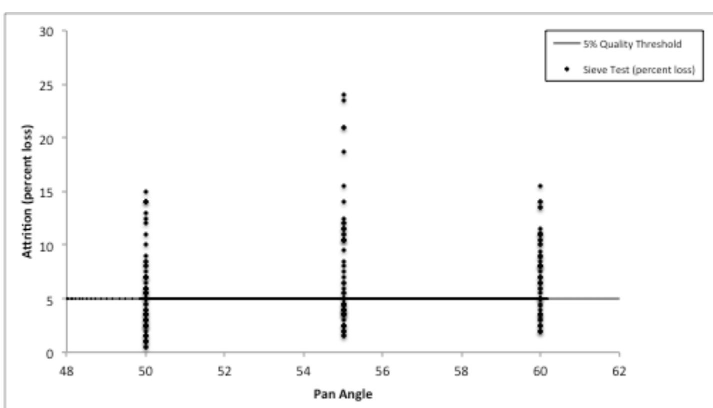


Figure 10- Pan angle and attrition in sieve test

In the bagged drop test the mean percent loss is 12.23%, while the average loss for the sieve attrition test lies just above the 5% threshold at 6.65% loss. Furthermore, the standard deviation for sieve test is much greater than that of the bagged drop test, 17.7 and 7.77, respectively. Lastly, while the two tests are measures of granule durability, they are not perfect substitutes for one another. The results for each test are only moderately correlated, r=.2370. This relatively low correlation is not surprising given that the mechanisms for attrition in the two tests are distinct and they are intended to predict durability in separate contexts (Reynolds, Fu, Cheong, Hounslow, & Salman, 2005). The sieve test is a measure of abrasion resistance and is more likely to serve to predict the product's durability during processing (conveyor belts, bagging, *etc*.) (Utsumi et al., 2001). The bagged drop test is a measure of stress from impact, crushing and granule-to-granule abrasive forces. As a consequence the test is a suitable predictor of granule durability "when fan-type fertilizer spreaders are used, when a material is discharged from an overhead conveyor into a bulk pile, and when bags of material are dropped during handling" (Rutland, 1986). From these results, it appears that the bagged drop test is the single best measure of granule durability. It measures both impact resistance and abrasion resistance simultaneously and requires the least complicated equipment (A scale, 2.00 mm sieve and a polyurethane bag). While it is advisable to use multiple tests for measuring granule strength and durability, we feel that of those methods used in this study, the bagged drop test results are the likely the most reliable and useful.

1.4 MODELS

We are interested in the exact relationship between process parameters and quality granules, which cannot be ascertained from the descriptive statistics alone. We tested two components of granule quality, size (as measured by the proportion of useful granules produced) and durability (measured by sieve test, RIT, and bagged drop test). To our knowledge, there have been no previous efforts to create a model with process parameters as a means of predicting granule quality. Other research such as Jovanovich *et al.* 2016 and Irshad *et al.* 2010, have reported results that give clues to the functional forms that may best represent the effect of a given parameter, but they did not venture to propose a model nor did they have the statistical power available to us in this study. The model specification that best describes the relationship between process parameters and granule quality is unknown. We will seek to systematically identify a suitable model in this section.

4.1 Bagged Drop Test Model

To start the process of constructing a model, we first generated a base linear model, with the three parts of the production process we systematically as regressors. The basic model is specified below.

$$AT = \beta_1 + \beta_2 BFP + \beta_3 AN + \beta_4 DT + e \qquad \text{Eq. 6}$$

Where *AT* is the percent loss due to attrition, *BFP* is the binder as a percent mass of the final product, *AN* is angle of the pelletizer pan and *DT* is the amount of drying time. We performed an ordinary least squares (OLS) regression to verify that all three parameters were significant at the at the $p < .05$ level. Jovanovic *et al* (2016) found that increasing the dosage of binder improved granule durability up to point, after which durability began to decline. This suggests that certain parameters may require a squared term to accurately depict the relationship (Hill et al., 2011). To check this, squared terms were systematically added to the model resulting in a total of 8 specifications. Additionally, Irshad *et al.* (2010) observed that pan rotation speed (RPM) acts on granule density, which is the same mechanism by which pan angle influences granule strength (Rahmanian et al., 2011). Thus, by adding terms for pan RPM and RPM squared, a total of 24 specifications were possible.

In order to determine which model is best, we used a process similar to that used in Simons *et al.* (2014) in which regressions were performed on multiple specifications, and the model with the lowest Akaike information criteria (AIC) were preferred. The AIC is a measure of goodness-of-fit, which protects against over specification by penalizing for unnecessary regressors (Akaike, 1981; Hill et al., 2011; A. M. Simons, Beltramo, Blalock, & Levine, 2014).

Table 4. Results from initial AIC tests of 24 model specifications

Specification	Binder^2	Angle^2	Dry. Time^2	RPM	RPM^2	Parameters Sig. at p < .05	Parameters Sig. at p < .1	Adj. R^2	AIC	BIC
(1)	Yes	Yes	Yes	Yes	--	--	Yes	**0.701**	**1039.399**	1064.940
(2)	Yes	Yes	Yes	--	--	Yes	Yes	0.698	1040.500	1062.851
(3)	Yes	Yes	Yes	Yes	Yes	--	--	0.700	1041.259	1069.995
(4)	Yes	--	Yes	Yes	--	--	Yes	0.696	1041.456	1063.807
(5)	Yes	--	Yes	--	--	Yes	Yes	0.692	1042.843	**1602.001**
(6)	Yes	--	Yes	Yes	Yes	--	--	0.695	1043.276	1068.819
(7)	--	Yes	Yes	--	--	--	--	0.599	1090.165	1109.323
(8)	--	Yes	Yes	Yes	--	--	--	0.601	1090.512	1112.863
(9)	--	--	Yes	--	--	Yes	Yes	0.596	1090.581	1106.545
(10)	--	--	Yes	Yes	--	--	--	0.601	1090.748	1109.906

a. Columns 2-5 indicate whether the variable specified was included in the model specification.

b. Adjusted R^2 and BIC (Bayesian information criteria) are additional measures of goodness-of-fit. Both penalize for additional regressors. Adjusted or pseudo-R^2 penalizes for extra regressors less severely than does AIC and BIC penalizes more severely than AIC (Hill et al., 2011).

We performed OLS regression on the 24 models described above and listed the ten models with lowest AIC in the table below. The base model is Eq. 6 and table 4 shows the additions of squared terms for *BFP, AN,* and *DT* as well as the RPM and RPM^2.

Plotting the residuals from the model specifications in table 4, we observed a high degree of heteroskedasticity and assumed that there may have been some omitted variables. We tested interaction variables for pan angle and RPM as well as drying time and binder. We found them to be significant and their inclusion in the model visibly reduced heteroskedasticity. We tested an additional 30 models consisting of these two interactions variables added to the ten models from table 4. The ten models with the lowest AIC are shown in the table 5 below.

Table 5, Results from AIC tests, including interaction variables

Specification	BFP^2	AN^2	*DT*	*DT*BFP*	*AN**RPM	RPM	RPM^2	Parameters sig. at p < .05	Parameters sig. at p < .1	Adj. R^2	AIC	BIC
(1)	Yes	Yes	Yes	Yes	Yes	Yes	--	Yes	Yes	**0.7358**	**1019.051**	1050.981
(2)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	--	--	0.7347	1020.69	1055.813
(3)	Yes	--	Yes	Yes	Yes	Yes	--	Yes	Yes	0.7305	1021.664	1050.400
(4)	Yes	Yes	Yes	Yes	Yes	--	--	Yes	Yes	0.7303	1021.791	1050.528
(5)	Yes	Yes	Yes	Yes	--	Yes	--	--	Yes	0.7293	1022.466	1051.183
(6)	Yes	--	Yes	Yes	Yes	Yes	Yes	--	--	0.7296	1023.239	1055.169
(7)	Yes	--	Yes	Yes	--	--	--	Yes	Yes	0.7257	1023.888	**1049.432**
(8)	Yes	--	Yes	Yes	Yes	Yes	Yes	Yes	Yes	0.7251	1024.275	1049.818
(9)	Yes	Yes	Yes	Yes	--	Yes	Yes	--	--	0.7280	1024.29	1056.220
(10)	Yes	--	Yes	Yes	--	Yes	--	--	Yes	0.7241	1024.948	1050.492

In order for a specification to be considered as the most suitable model, it must not only have the lowest AIC, but we also hold that all regressors should be significant at the $p < .05$ level. Furthermore, it must adhere to our theoretical understanding of the relationships between the production parameters and granule durability. (Hill et al., 2011)

From these selection criteria, it is clear that specification 1 from table 5 is the most suitable model. The model suggests that increasing the dosage of binder will increase granule durability at a decreasing rate similar to findings of Fu *et al.* (2005). That is, increasing binder from 1% of the final product to 2% of the final product will improve granule durability greater than, say, an increase from 4% to 5%.

These results largely agree with Jovanovic *et al* (2016). We find that the increased pan angle decreased granule strength, likely a consequence of the increased granule density resulting from increased residency (Irshad, Sharif, Khan, & Rizvi, 2010; Reynolds et al., 2005). While this model contains a squared term for pan angle, the second best model meeting our criteria (specification 3 in table 5,which in fact has a lower BIC) lacks the squared term. Drying time, like additional binder solution increases granule durability but at a decreasing rate. This may be due to the fact that as the granule dries, the moisture content of the granule decreases, which in turn makes it more brittle and thus prone to attrition (Tousey, 2002).

Table 6. Results from preferred model for bagged drop test

Parameter	Coefficent	S.E.	95% Confidence Interval	
Binder	-19.65421**	1.928832	-23.46176	-15.84666
Binder^2	2.276349**	0.2861723	1.711441	2.841258
Angle	7.82355**	2.875266	2.147727	13.49937
Angle^2	-0.0532295*	0.0253402	-0.1032516	-0.0032074
Drying Time	-0.5569014**	0.0430297	-0.6418426	-0.4719601
Drying Time^2	0.002698**	0.000271	0.0021631	0.0032329
RPM	3.220371*	1.51202	0.2356182	6.205124
Binder x Dry Time	0.0299742**	0.0067964	0.016558	0.0433904
Angle X RPM	-0.0628834*	0.0276492	-0.1174634	-0.0083035

*- significant at $p < .05$; **- significant at $p < .01$

Increasing pan RPM appears to increase attrition in the bagged drop test. This is likely a consequence of breakage rate of granules inside the pan during the growth process exceeding the rate at which granules can effectively agglomerate and densify (Reynolds et al., 2005). The interaction variable of rotation speed and pan rpm could be reasonably called "agitation intensity" while decreasing breakage, which increases densification and as a consequence, granule strength (Schæfer, 2001). Lastly, the mechanism through which the interaction of binder and drying time is not well understood. It may be that granules with higher binder content and moisture content when dried, lock in that moisture, which can compromise quality (Tousey, 2002).

4.2 Sieve Attrition Test Model

The process for selecting the attrition test model is identical to that used for the bagged drop test. We tested a total of 54 models, but unlike the bagged drop test model, the interaction variables were not significant at even the $p < 0.1$ significance level. As a consequence, they were not included as candidate models. Based upon the selection criteria from above, it is clear that specification 1, having the highest pseudo-R^2, lowest AIC and BIC is the preferred candidate for our model. Not surprisingly, excluding the insignificant interaction variables, the model for sieve attrition has the exact same parameters as the model for the bagged drop test. The lower *pseudo-r^2* value tells us that there is a large amount of variance that remains unexplained by this model and speaks to the potential effectiveness of the sieve test as a measure of durability.

Table 7. Top ten results from AIC tests for sieve attrition test models

Specification	BFP^2	AN^2	DT^2	*RPM*	RPM^2	Parameters Sig. at p = .05	Parameters Sig. at p = .1	Adj. R^2	AIC	BIC
(1)	Yes	Yes	Yes	Yes	--	Yes	Yes	**0.456**	**948.387**	**973.931**
(2)	Yes	Yes	Yes	Yes	Yes	--	--	0.453	950.310	979.047
(3)	Yes	--	Yes	Yes	--	Yes	Yes	0.439	952.885	975.236
(4)	Yes	--	Yes	Yes	Yes	--	--	0.436	954.843	980.387
(5)	Yes	Yes	Yes	--	--	Yes	Yes	0.432	954.949	977.300
(6)	Yes	--	Yes	Yes	--	Yes	Yes	0.413	959.872	979.029
(7)	Yes	Yes	--	Yes	--	Yes	Yes	0.403	963.897	986.248
(8)	Yes	Yes	--	Yes	Yes	--	--	0.400	965.827	991.371
(9)	Yes	--	--	Yes	--	Yes	Yes	0.387	967.802	986.960
(10)	Yes	Yes	--	--	--	Yes	Yes	0.381	969.683	988.840

Table 8. Results from preferred model for sieve attrition test

Parameter	Coefficent	S.E.	95% Confidence Interval	
Binder	-10.74816**	1.558607	-13.82462	-7.671702
$Binder^2$	1.396543**	0.2355835	0.931536	1.86155
Angle	5.988749*	2.300634	1.447638	10.52986
$Angle^2$	-0.0526363*	0.0209338	-0.0939565	-0.0113161
Drying Time	0.1664317**	0.032185	0.1029032	0.2299603
Drying $Time^2$	-0.0009384**	0.0002239	-0.0013802	-0.0004965
RPM	-0.2714663*	0.0937801	-0.4565743	-0.0863582

*- significant at $p < .05$; **- significant at $p < .01$

There are some notable differences in the signs and magnitudes of certain process parameters' effect on attrition during sieve test as compared to the model generated for the bagged drop test. The effect of binder and pan angle on attrition and the mechanism through which they affect attrition are assumed to be equal to those discussed during the model for bagged drop test. The opposite signs, however, are observed for drying time and pan RPM in this model. It may be useful remember that different tests for granule strength or durability, for the most part, cannot be compared with each other (Reynolds et al., 2005). The mechanisms for breakage and attrition are different for different tests and the physical properties affecting the outcomes are likely distinct.

It has been observed that increased granulator RPM can decrease the sphericity and smoothness of granules (Eliasen, Kristensen, & Schaefer, 1999), which in turn increases the attrition rate in sieve-type attrition tests (Bemrose & Bridgwater, 1987). To picture how this lower sphericity might affect attrition in the sieve test, it is useful to imagine sand-paper removing the rough edges on a wooden board. A similar mechanism is at play here: the imperfections (non-spherical edges and points on the granule) are easily removed upon contact with the sieve.

According to the model, drying time increases attrition at a decreasing rate. It stands that decreased moisture content would increase granule hardness (Hardesty & Ross, 1938), and it may, as a consequence, make the granule more fragile, increasing the loss due to attrition. Additional research is required to identify the mechanism through which drying time affects attrition in the sieve test, for at the time of analysis we could find no previous work that might explain our results.

4.3 Percent Useful Granules

In their approach to describe particle size distribution, the fertilizer industry typically only uses two parameters and complex equations that are unlikely to be adopted for routine use (Allaire & Parent, 2003). Our goal in this section is to generate a simplistic model that is more intuitive and may be more readily applicable to the daily operations of a small-scale fertilizer producer.

$$U = \beta_1 + \beta_2 BSOL + \beta_3 AN + \beta_4 RPM + e \qquad \text{Eq. 7}$$

In the model, *U* is the yield of useful granules; *BSOL* is the quantity of binder solution added during pelletization (mL/kg); *AN* is the pan angle and *RPM* is the pan RPM. To determine which parameters should be included in subsequent iterations of the model, we performed an OLS regression. The initial results showed that pan RPM had no effect, so it was discarded. After reducing the model to two parameters, squared terms were systematically added to the model corresponding to Eq. 7 but with the *RPM* term removed. Of the resulting four models, two models had regressors that were all significant at a $p < .05$: the base model with two parameters and another with a squared term for binder solution.

Table 8. Model specifications for yield of useful granule

Specification	$BSOL^2$	Adj. R^2	AIC	BIC
(1)	Yes	0.6588	**306.4786**	**312.8127**
(2)	--	0.5523	315.3643	320.1148

It is clear, based on our selection criteria that specification (1) is the most suitable model.

Table 9. Results from preferred for yield of useful granules

Parameter	Coefficent	S.E.	95% Confidence Interval	
Binder Sol.	-0.357493**	0.08541578	-0.531	-0.184
Binder Sol.^{2}	0.0002172**	0.0000646	0.0000856	0.0003487
Pan Angle	2.889126**	0.6637158	1.537181	4.241071

In the model, increasing binder solution decreased the yield of useful granules at a decreasing rate. This result agrees with the findings of other authors who observed that addition binder solution increased mean granule size, thus reducing the yield of useful granules (Jovanović et al., 2016; Pujara, 2007). It is also observed that lower pan angles result in low yields of useful granules. The mechanism for this outcome is again the increase in average granule size (Delwel & Veer, 1978)

1.5 Conclusion

We produced durable granules from bone char fertilizer in a controlled laboratory setting using locally sourced binder in Jimma, Ethiopia. The production system is less sophisticated than would be found in a commercial fertilizer production facility, but our findings provide sufficient evidence that the production of bone char fertilizer granules is feasible in this setting and that further resources are warranted to further develop the technology and processes for scale.

The fertilizer granules produced had larger median diameter and wider size distributions than would likely be found in fertilizers from the United States or Europe. We hypothesize, however, that this problem will not significantly affect marketability or use efficiency of granulated bone char because virtually all smallholder farmers in Ethiopia apply fertilizer by hand, and problems resulting from poor granule size distributions are typically associated with mechanical spreaders.

Of the granule strength tests we performed, we believe that the bagged drop test is the most useful and economical test for the relative durability and strength of fertilizer granules. We also determined that the RIT is not appropriate as a final measure of granule strength, though it may be appropriate for very early stages in developing fertilizer granules.

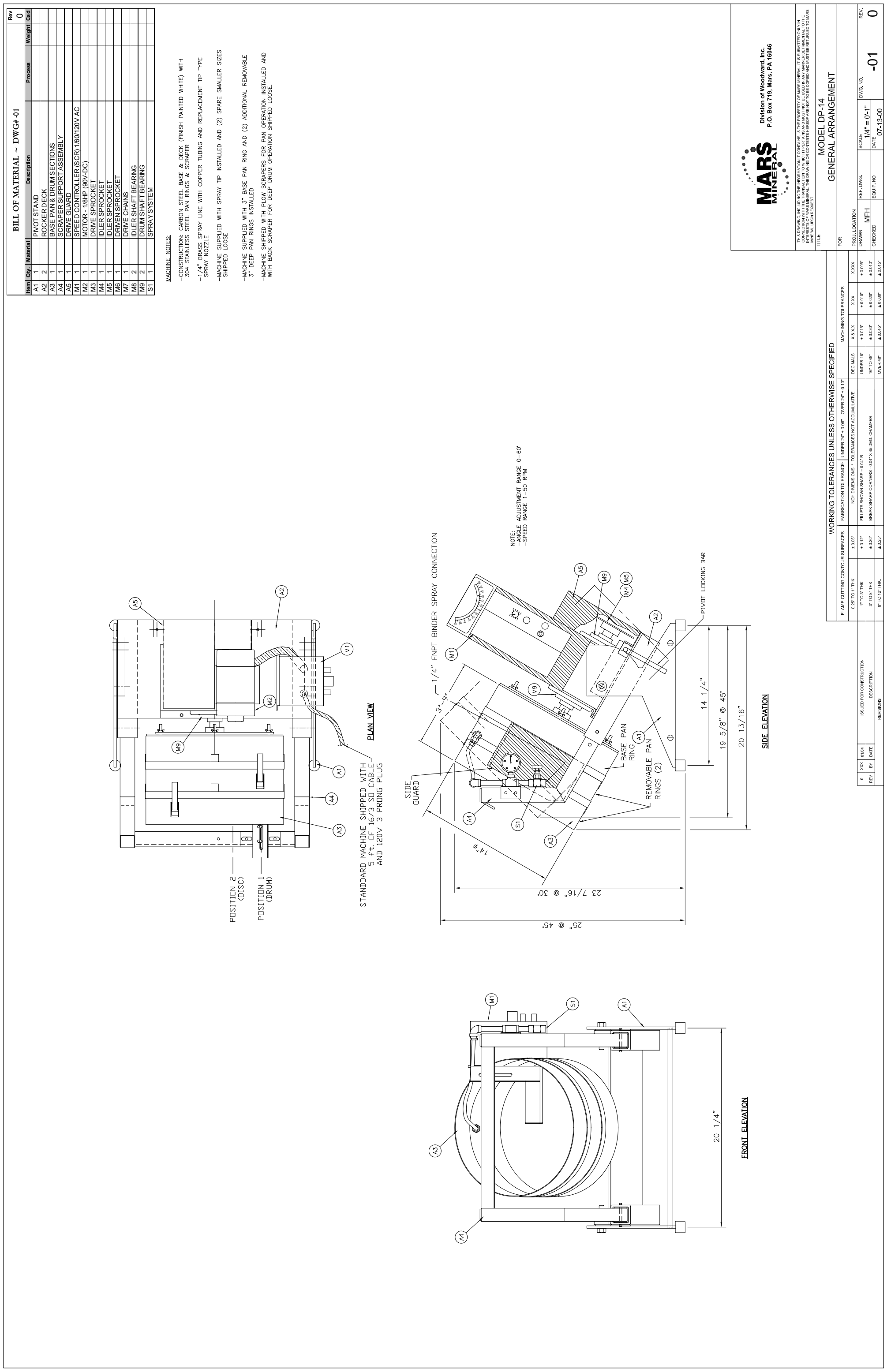
We proposed models for predicting the outcomes for each the bagged drop test, sieve attrition test and the yield of useful granules as functions of process parameters. The models offer insight as to how individual production processes can be manipulated to influence granule quality, which is essential to optimize a granulation system.

While previous research corroborated many results from our modeling exercise, additional work is warranted to verify the physical mechanisms through which process parameters ultimately affect granule durability and size distribution. Future research should explore the effect of particle size distribution of the powdered bone char on granule quality. Additional work should be done to identify alternative and cost-effective binders as well as the effects of binder viscosity and drying conditions. While these factors were not included in this study, they almost certainly would impact granule quality and process efficiency.

We have demonstrated that bone char fertilizer is a suitable candidate for granulation and we have a generated a model that guides efforts to improve the granulation process. These findings bring bone char closer to market and significantly increase the likelihood that bone char fertilizer will be commercially available in Ethiopia in the near future.

APPENDIX D

Diagram of DP-14 Pelletizer



APPENDIX E

Description of Fertilizers in WTP Auction (English)

DAP:

"This is a five kilogram bag of diammonium phosphate. Diammonium phosphate has been the most heavily used fertilizer in Ethiopia for many years and it remains the most commonly used phosphorus fertilizer in the world. It is mostly imported from China and repackaged in Ethiopia. This 5kg bag of DAP contains 900 grams of Nitrogen and 1.0 Kg of Phosphorus.

DAP is an excellent source of Phosphorus (P) and nitrogen (N) for crop plants. It's highly soluble and thus dissolves quickly in soil to release plant-available phosphate and ammonium. Many soils, however, are highly acidic and when soils are highly acidic, much of the phosphorus in DAP may not be available to your crop plants."

MIX:

"This is a 9 kg bag of fertilizer that contains a mixture of urea and bone char. This 9 kg bag contains the same amount of nitrogen and phosphorus as that 5 kg bag of DAP. It contains 0.9 kg of Nitrogen and 1.0Kg of Phosphorus.

The urea component of this fertilizer provides the nitrogen. Urea is the most commonly used solid nitrogen fertilizer in the world. When applied properly and incorporated quickly into the soil, urea is an excellent source of nitrogen.

The bone char component in this fertilizer contains phosphorus, calcium and some micronutrients. Bone char fertilizer is a sterile and safe product made here in Ethiopia from charred animal bones. It was produced with Ethiopian inputs, labor and equipment. In addition to providing Phosphorus and Calcium, bone char may reduce the acidity of your soil, which, depending on the soil of your farm, can improve the ability of your crops to absorb phosphorus in the future. The effect of bone char on yields is not as well understood as DAP's effect on yield, but research indicates that bone char is as effective as imported phosphorus fertilizer in acidic soils."

BC:

"This is a 7kg bag of a fertilizer called bone char. Bone char fertilizer is a sterile and safe product made here in Ethiopia from charred animal bones. It was produced with Ethiopian inputs, labor and equipment. This fertilizer contains phosphorus, calcium and some micronutrients. It does not contain any nitrogen, a vital nutrient for plant growth. If you want to apply nitrogen, you must purchase another fertilizer separately. This bag of fertilizer contains 1.0 Kg of Phosphorus.

In addition to providing Phosphorus and Calcium, bone char may reduce the acidity of your soil, which, depending on the soil of your farm, can improve the ability of your crops to absorb phosphorus in the future. The effect of bone char on yields is not as well understood as DAP's effect on yield, but research indicates that bone char is as effective as imported phosphorus fertilizer in acidic soils."

APPENDIX F

Description of Fertilizers in WTP Auction (Amharic)

DAP:

ይህ አምስት ኪሎ ግራም የሚመዝን የ ዳፕ ማዳበሪያ ነዉ፡፡ ይህ ማዳበሪያ በኢትዮጵያ ለብዙ አመታት በሰፋት ጥቅም ላይ የዋለ ሲሆን በአለም ላይም በስፋት ጥቅም ላይ እየዋለ ያላ የ ማዳመሪያ አይነት ነዉ፡፡ አብዛኛዉን ግዜ ጥሬ እቃዉ ከቻይና እየገባ በሀገራችን ታሽጎ ለተጠቃሚ ይደርሳል፡፡ ይህ 5 ኪሎ ግራም የ ዳፕ ማዳበሪያ በዉስጡ 900 ግራም ናይትሮጅን እና 1.0 ኪሎ ግራም ፎስፈረስ ይይዛል፡፡

ዳፕ ለተክሎች እድገት ጠቃሚ የሆኑትን ናይትሮጅን እና የፎስፈረስ የተባሉ ንጥረ ነገሮችን የያዘ ነዉ፡፡ እነዚህ ንጥረ ነገሮች በቀላሉ የሚሟሙ ስለሆኑ በአፈር ዉስጥ ከዉጋር በፍጥነት በመዋሃድ ተክሎች በቀላሉ እና በፍጥነት ሊጠቀሙበት ወደሚችሉት ፎስፌት እና የአሞኒየም ይቃየራል፡፡ ይሁን እንጂ በጣም አሲዳማ በሆኑ የአፈር ዐይነቶች ላይ አብዛኛዉ በዳፕ ዉስጥ የሚገኘዉ የፎስፈረስ ንጥረ ነገርን ተክሉ በቀላሉ ሊጠቀመዉ አይችልም፡፡

MIX:

ይህ ዘጠኝ ኪሎ ግራም የሚመዝን የተፈጥሮ የአጥንት ማዳበሪያ እና የዩሪያ ማዳበሪያ ዉህድ ነዉ፡፡ በዉስጡ ከዚህ በላይ ከተጠቀሰዉ አምስት ኪሎ ከሚመዝነዉ የ ዳፕ ማዳበሪያ ጋር እኩል የሆነ 900 ግራም ናይትሮጅን እና 1.0 ኪሎ ግራም ፎስፈረስ ይገኝበታል፡፡

በዚህ ዉህድ ዉስጥ የሚገኘዉ ዩሪያ ናይትሮጅን የተባለን ንጥረ ነገር የሰጠናል፡፡ የዩሪያ ማዳበሪያ በአለማችን መስፋት ጥቅም ላይ የዋለ ጠጣር የናይተሮጅን ማደበሪያ ነዉ፡፡ በአግባቡ እና በፍጥነት ከአፈር ጋር ከተደባለቀ ዩሪያ በጣም ጥሩ የ ናይተሮጅን ምንጭ ነዉ፡፡

በዚህ ዉህድ ዉስጥ የሚገኘዉ የተፈጥሮ የአጥንት ማዳበሪያ እንደ ፎስፈረስ፣ ካልሲየም እና ለተክሎች እድገት አሰፈላጊ የሆኑ ንጥረ ነገሮችን በዉስጡ ይዟል፡፡ ይህ የተፈጥሮ የአጥንት ማዳበሪያ ምንም አይነት ጉዳት የሌለዉ እና ከበሽታ አምጪ ህዋስ የጸዳ በ ሀገራችን ኢትዮጵያ የተመረተ ሀገር በቀል የተፈጥሮ ማዳበሪያ ነዉ፡፡ ይህ የተፈጥሮ ማዳበሪያ ከሚገኘዉ የ ፎስፈረስ እና ካልሲየም በተጨማሪ የአፈርን አሲዳማነትን በመቀነስ ተክሎች የፎስፈረስ ማዳበሪያን ከአፈር ዉስጥ በቀላሉ እንዲጠቀሙ ያስችላቸዋል፡፡ የዚህ የተፈጥሮ የአጥንት ማዳበሪያ በተክሎች ላይ ያለዉ አዉነታዊ ተጽኖ ልክ የዳፕን ያህል በጥልቀት አይታወቅም፣ ይሁን እነጂ እሰካሁን የተደረጉት ጥናቶች የተፈጥሮ የአጥንት ማዳበሪያ በ አሲዳማ አፈር ላይ ልክ እንደ ዳፕ ተመሳሳይ አሉታዊ ተጽኖ እነዳለዉ ያሳያሉ፡፡

BC:

ይህ ሰባት ኪሎ ግራም የሚመዝን በ ሀገራችን ኢትዮጵያ ከእንስሳት አጥንት የተመረተ ሀገር በቀል የተፈጥሮ ማዳበሪያ ነዉ፡፡ በዉስጡ ፎስፈረስ ፤ ካልሲየም እንዲሁም ሌሎች ለተክሎች አስፈላጊ የሆኑ ንጥረነገሮች ይገኙበታል፡፡ ይህ የተፈጥሮ የአጥንት ማዳበሪያ በዉስጡ ናይትሮጅን የያዘ ስላልሆነ፤ ይህን ንጥረነገር የምናገኝበትን የ ዩሪያ ማዳበሪያ መግዛት ያስፈልጋል፡፡ በዚህ ከረጢት ዉስጥ 1.0 ኪሎ ግራም ፎስፈረስ ይገኝበታል፡፡

ይህ የተፈጥሮ ማዳበሪያ ከሚገኘዉ የ ፎስፈረስ እና ካልሲየም በተጨማሪ የአፈርን አሲዳማነትን በመቀነስ ተክሎች የፎስፈረስ ማዳበሪያን ከአፈር ዉስጥ በቀላሉ እንዲጠቀሙ ያስችላቸዋል፡፡ የዚህ የተፈጥሮ የአጥንት ማዳበሪያ በተክሎች ላይ ያለዉ አዉነታዊ ተጽኖ ልክ የዳፕን ያህል በጥልቀት አይታወቅም፣ ይሁን እነጂ እሰካሁን የተደረጉት ጥናቶች የተፈጥሮ የአጥንት ማዳበሪያ በ አሲዳማ አፈር ላይ ልክ እንደ ዳፕ ተመሳሳይ አሉታዊ ተጽኖ እነዳለዉ ያሳያሉ፡፡

APPENDIX G

Survey administered to farmers in WTP experiment

I. Demographic & Economic Data

Participant Name:________________

1.	2.	3.	4.	5.	6.
What is the sex of the individual? (Do not ask participant this question.) Female…1 Male…….0	**What is your Age?** If the participant does not know their exact age, ask them to estimate. Years	**Are you the head of your household?** Yes…1 No…0	**How many years have you been working as a farmer?** Years	**How many years of school did you attend in your lifetime?** Years	**How many people normally live and eat meals in your household?**

7.	8.	9.	10.	11..
During the last 12 months, how much income has your household generated, either through selling your harvest or non-farm work? Answer in ETB	**At this time, how many cattle or oxen do you own?**	**At this time, how many sheep and goats do you own?**	**What is the size of your farm?** **Please include all the land you cultivate, including smaller or less productive lands.** Answer in hectares	**Which statement mostly accurately reflects your rights to the land you cultivate?** Inherited kebele land…..1 Mostly Inherited kebele land but I rent another, smaller plot of land …..…....2 I have some inherited kebele land, but **Most** of the land is rented……………....3 I am squatting on the land I am cultivating. ……..4

II. Farming Practices and Knowledge

Participant Name:________________

1.	2.	3.	4.	5.	6.	7.
Do you have any irrigation system for your crops? Yes.....1 No......0	**What is your main crop?** *What crop generates the most income?* Corn…………1 Soybean……..2 Teff………….3 Wheat……….4 Coffee……….5 Chaat……….6 Other……….7	**During a normal planting season, how much do you spend on fertilizer?** Anser in ETB	**During a normal planting season, how many kg of fertilizer do you purchase?** Answer in Kg	**During the last three planting seasons, how many times did you purchase fertilizer?**	**During the last 3 years how many times have you tried to purchase fertilizer but were unable to find a fertilizer on the market?**	**Do you use other amendments such as manure or compost on your farm?** Yes.....1 No......0

8.	9.	10.	11	12.
Do you believe that a domestically produced fertilizer or an imported fertilizer from China is more likely to be effective? Import......... 1 Domestic.....0	**Have you ever heard of bone char fertilizer?** If "Yes", **How many people do you know that have used bone char fertilizer in the past** Yes.....1 No......0	How strongly do you agree with the following statement: **"I would pay extra money for a fertilizer if I knew it would be available on the market when I needed it most."** Please choose a number between one and ten that best represents your opinion. For example, "1" means I already have access to fertilizer whenever I need it and "10" means that I would pay a lot if I knew I could buy that fertilizer whenever I needed it for my crops.	On a scale of 1-10, **how important is fertilizer for improving your income ?** *Please choose a number between one and ten that best represents your opinion. For example, "1" means that fertilizer is too expensive and is not worth the investment and "10" means that without fertilizer, your yield will be too small to support you or your family.*	**How often are you visited by a development agent?** More than once per month…..……........1 Once per month …...2 1-3 times per year.…3 Never……………....4